11th fatigue design

ABSTRACT BOOK

International Conference

19 & 20 November 2025 - France

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11th fatigue design

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Fabien Lefebvre

On behalf of the Fatigue Design 2025 International Scientific Committee and Organising Committee, we are delighted to welcome you all to the 11th edition of Fatigue Design, which takes place at Cetim, Senlis, France, on 19 and 20 November 2025. This special anniversary marks the 20th year of our conference series, providing a unique opportunity to reflect on the journey and evolution of Fatigue Design since its inception.

This year, we are proud to place a spotlight on the theme of **the fatigue in the Green Economy**, recognising the growing importance of sustainable engineering in addressing global challenges. Accordingly, the conference will particularly focus on how advances in fatigue design can contribute to more environmentally responsible industrial solutions.

The relevance of the conference remains undiminished, prompting us to revisit the synergy between 'Fatigue'—the resistance of materials and structures to repeated loading and damage—and 'Design', which now more than ever requires innovative approaches to meet the stricter demands for durability, lightweight structures, and life extension. With increasing emphasis on weight reduction, performance improvement, and the evaluation of remaining service life, the risk of fatigue failure is a central concern in contemporary mechanical design. As such, the concept of 'Fatigue Design' has become central, moving beyond simple post-design verification.

Organised by Cetim and its partners, the 11th Fatigue Design 2025 International Conference presents the latest breakthroughs in design methodologies, state-of-the-art testing techniques, and advanced tools for evaluating and extending the fatigue life of industrial equipment, with a clear focus on industrial applications and sustainability.

This year's congress will also highlight the vital role of fatigue design in supporting the green economy, including dedicated sessions on:

- Fatigue under severe environmental conditions (such as hydrogen, corrosion, and low temperatures)
- Fatigue of assemblies
- Fatigue life extension and residual life assessment

These themes will allow participants to exchange knowledge and best practices that contribute to the reduction of environmental impact and the advancement of sustainable engineering solutions.

Building on the integration of Big Data and Artificial Intelligence from previous editions, these cutting-edge topics will remain central, alongside new discussions related to H2 fatigue behaviour and other emerging challenges. The scientific and technical programme will also encompass:

- Additive manufacturing
- Complex loading scenarios
- Composites and elastomers
- Contact fatigue and fatigue in transmission systems
- Damage tolerance and fatigue life
- Experimental and numerical design and validation methods
- Reliability-based approaches and probabilistic methods
- Influence of manufacturing processes on fatigue analysis (including the effects of microstructure, welding, and stress relief techniques)
- Vibration fatigue behaviour

Presentations will spotlight the most recent developments and experimental and simulation techniques, as well as the engineering tools that are helping to shape the future of industrial applications. As always, the conference is organised in collaboration with Elsevier, with proceedings published in Structural Integrity Procedia on ScienceDirect, ensuring global reach and impact.

This edition will feature over 100 oral presentations, with a significant proportion delivered by industry experts, as well as new sessions and exhibition spaces to foster engagement. Poster sessions and exhibition booths will offer further opportunities for interaction among scientists, engineers, PhD students, and solution providers. The digital platform will continue to enable participation for those unable to attend in person, ensuring the widest possible dissemination of knowledge and discussion.

We extend our sincere thanks to the International Scientific and Organising Committees for their invaluable expertise, as well as to all authors, delegates, exhibitors, and sponsors for their contributions. Special appreciation is due to the SF2M Fatigue Commission and our colleagues at Cetim for their dedication and commitment to the success of the conference.

We wish you a most enjoyable stay in Senlis and look forward to a stimulating and inspiring Fatigue Design 2025, as we celebrate 20 years of collaboration and progress in this vital field.

Fabien Lefebvre

Cetim Scientific Advisor
Chairman Organising Committee Fatigue Design 2025

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Poster Award 2025

The poster session of the 11th edition of the Fatigue Design conference, celebrating 20 years of the event, will feature more than 20 posters presenting cutting-edge research from academia and industry.

This session provides an excellent opportunity for technical and scientific exchanges among researchers, engineers, industrial experts, and PhD students.

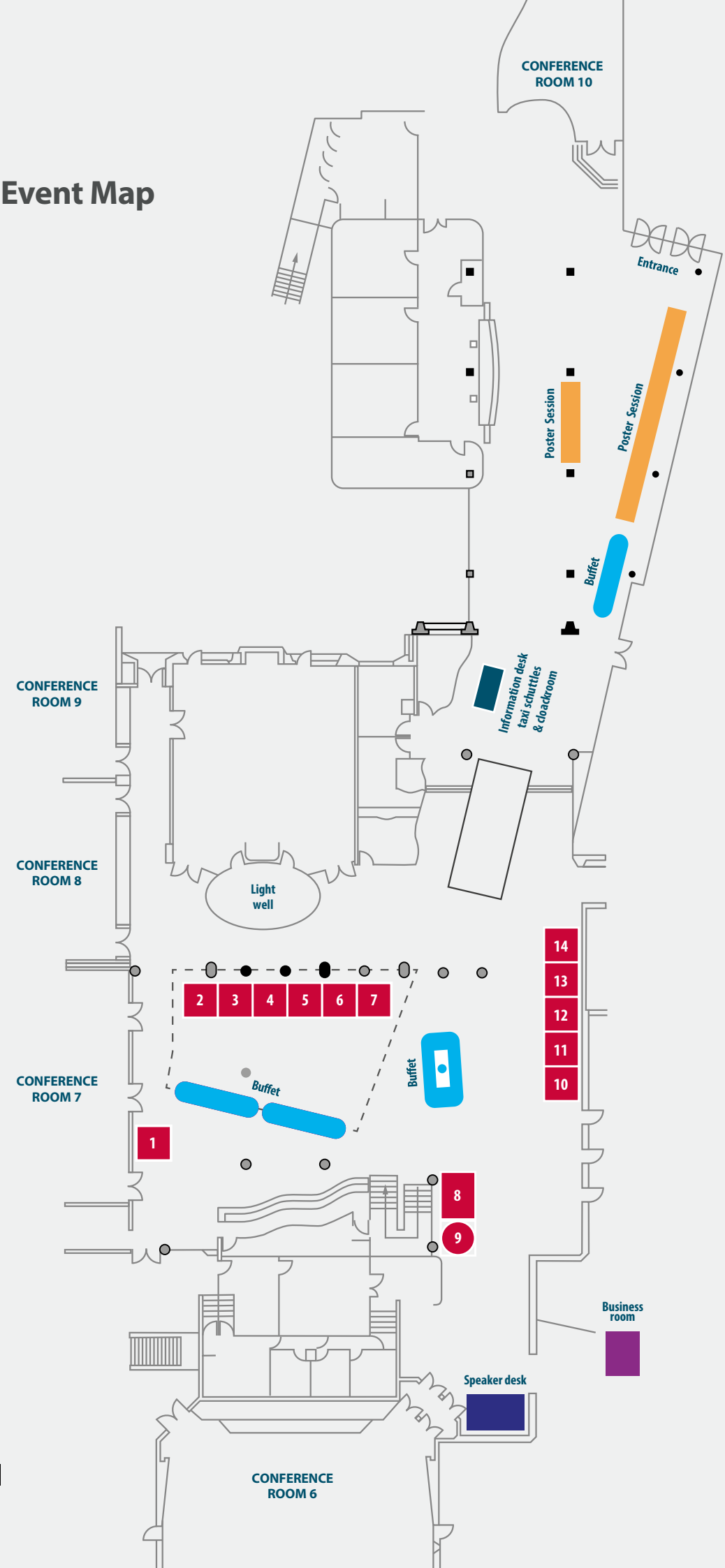
To recognize and promote outstanding research and to encourage young researchers and PhD students, a Poster Award will be presented. The Poster Award Committee will select the best poster based on scientific quality, originality, and technical relevance.

The winner of the Best Poster Award will receive a Certificate of Recognition and an iPad©.

During the 10th Fatigue Design 2023 conference, the Poster Award was presented to Marie Bouyx from ONERA, Châtillon, France, and Ecole Centrale Nantes, Nantes, France, for her work entitled:

“Numerical modeling of high-frequency fatigue testing for short crack propagation from tailored defect. »

Event Map



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Content

Plenary Session

S01 Additive Manufacturing

S02 Big Data and Artificial Intelligence

S03 Complex Loadings

S04 Composite and Elastomers

S05 Contact Fatigue and Fatigue in Transmission System

S06 Damage tolerance, Fatigue Life Extension and Residual Life Assessment

S07 Experimental and Numerical Design and Validation Methods

S08 Fatigue and Manufacturing Process

S09 Fatigue of Assemblies

S10 Fatigue under Severe Environmental Conditions

S11 Reliability-based Approaches and Probabilistic Methods

S12 Thermal and Thermo-mechanical Fatigue

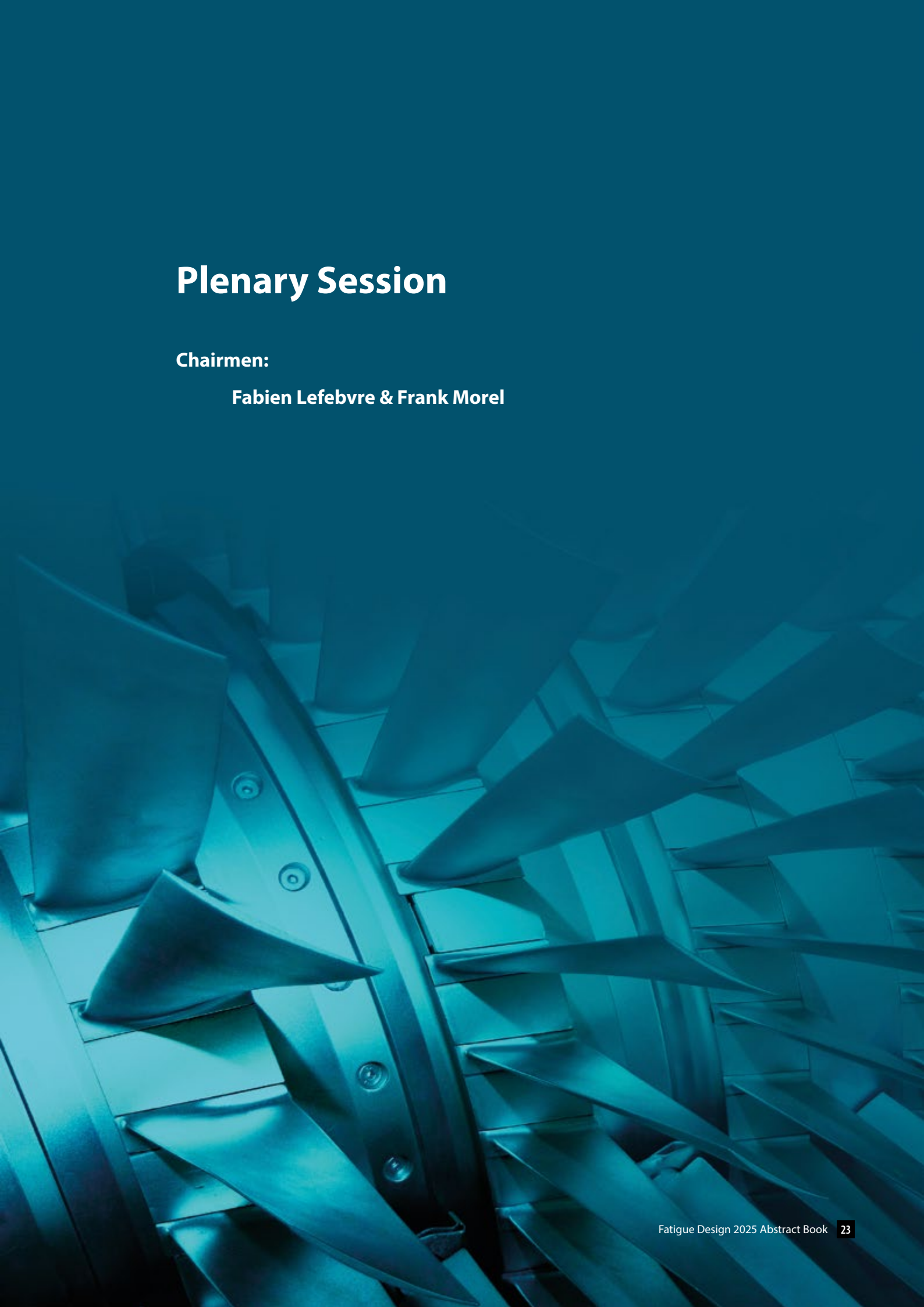
S13 Vibration Fatigue

Poster Session

Plenary Session

Chairmen:

Fabien Lefebvre & Frank Morel



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FATIGUE DESIGN 2025

FD25-150

Hydrogen-Resistant High-Strength Steels Beyond 1 GPa and Data-Driven Prediction of Fatigue Crack Growth in Hydrogen Gas

Hisao Matsunaga

Department of Mechanical Engineering, Kyushu University, Fukuoka, Japan

Hydrogen infrastructure requires structural materials that combine very high strength with reliable resistance to hydrogen gas embrittlement. Previous fatigue studies of quenched-and-tempered low-alloy steels have established a practical design upper bound of about 900 MPa in tensile strength for high-pressure hydrogen, because fatigue crack growth accelerates sharply and, at higher strengths, exhibits strong time dependence at low loading frequencies. In air, crack growth remains cycle-controlled, whereas in hydrogen the transition above approximately 900 MPa undermines conventional life prediction based on pressurization cycles. These trends, observed for martensitic steels from 0.001 to 1 Hz, motivate alloy- and process-design strategies that decouple high strength from hydrogen sensitivity.

This presentation reports the discovery and validation of hydrogen-resistant high-strength steels that surpass the long-standing 900 MPa limit. By combining ausforming-based thermomechanical processing with targeted composition tuning, we manufactured candidate steels that achieve an ultimate tensile strength of approximately 1200 MPa while exhibiting excellent resistance to hydrogen-induced acceleration of fatigue crack growth. The improvement was confirmed across multiple alloy variants, indicating robustness of the processing and design concept rather than dependence on a single outlier material. These results expand the design window for hydrogen service toward significantly higher strength levels.

Emphasis will also be placed on the activation mechanisms underlying hydrogen tolerance revealed by comparative microstructural and crack-tip analyses. The talk will discuss how controlled microstructural states obtained by the coupled process-composition route mitigate hydrogen-assisted damage processes at the crack tip. These insights provide a physically grounded basis for materials selection and for translating laboratory measurements into engineering allowables for hydrogen gas environments.

Finally, we introduce a suite of data-driven fatigue crack growth prediction programs tailored for hydrogen gas. The programs integrate experimentally curated da/dN information and predict hydrogen-environment fatigue crack growth behavior for individual materials while supporting three primary design tasks: life prediction under service loading, rational determination of required wall thickness for target reliability, and automated screening of candidate materials against performance constraints. We have developed multiple programs tuned to distinct objectives and use cases, and example workflows will be demonstrated to show how these programs shorten the iteration cycle between materials development and structural design, thereby enabling consistent, evidence-based decisions for hydrogen infrastructure components.

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FATIGUE DESIGN 2025

FD25-151

Fatigue life assessment in nuclear power plants: How could feature tests help improve design codes?

Clémentine Jacquemoud

CEA Saclay, Gif-sur-Yvette, France

In the nuclear industry, the regulator imposes periodical assessments of the Nuclear Power Plant's (NPP) « good health » for everyone's safety, and not only before commissioning or in case of an incident.

Structural integrity assessment codes provide a set of guidelines and methodologies to follow in addressing safety cases. Either French design codes RCC-MRx, RCC-M, and RSE-M, or the UK's R5 and R6, rely on analytical and semi-analytical methods to assess fracture, fatigue, and creep-fatigue life. These guidelines are purposely defined to be fairly simple for industry use (elastic analysis and plastic correction) and to cover all NPP situations in a conservative way, so that all uncertainties are accounted for and margins ensured.

But in some cases, when applied to NPP component geometries and realistic transients, they can be overly conservative, which is not always appropriate and justified. For this reason, they are continuously evolving, but the addition of new methods requires robust technical justifications.

Particularly, material data and characteristics, criteria being obtained from tests on laboratory specimens (uniaxial specimens, CT specimens, Charpy, …), understanding their transferability from laboratory specimens to plant-relevant components has been a key issue for decades.

When addressing this issue combined with conditions and parameters as complex as environmental assisted fatigue, variable amplitude loading in biaxial conditions, weld residual stress effect, etc…, feature tests become the best candidates to provide a mechanistic understanding of the differences between small scale lab tests and full component, gain a better knowledge on particular uncertainties and questions remaining opened (mean stress, triaxiality effect, closure effect, stress in singularities, …).

While their design and realisation are a real challenge to ensure high-quality results, these tests bring precious knowledge to improve our abilities to handle safety cases accurately.

As a first illustration, tests on notched and tubular specimens combined with a complex experiment in biaxial cycling loading in a Pressurised Water Reactor environment brought essential data to highlight the reduction in environmental effect and overload effect in biaxial loading conditions compared to uniaxial ones.

A second example concerns weld residual stress effects on fatigue propagation, where component-scale pipes are tested to evaluate the difference in mean stress, stress re-distribution and closure effect between the pipe and CT specimens. In this case, the challenge is to accurately measure the stress field and the resulting surface crack geometry at every step of the propagation. This must be achieved using a non-destructive method such as neutron diffraction. This would generate the knowledge to account for residual stress more realistically in fatigue assessment of components.

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FATIGUE DESIGN 2025

FD25-152

Tomorrow's World: Fatigue and Reliability Qualification in the Green Economy

Andrew Halfpenny

Hottinger Bruel & Kjaer UK Ltd, Rotherham, United Kingdom

This keynote provides a cross-sector view of fatigue and reliability in the green economy. It begins with a review of current challenges in electrification, hydrogen systems, fusion energy, new materials, and circular manufacturing. It then presents a modern framework for fatigue and reliability engineering, combining traditional methods with digital tools across three key areas:

1. Design Space: The design space is evolving rapidly. Physics-informed AI is enhancing tools like Failure Mode and Effects Analysis (FMEA). Emerging FMEA should include the Voice of Business, Voice of Customer, and Voice of Regulator, along with qualification test requirements for each failure mode. These elements align technical risks with broader stakeholder needs and ensure reliability targets are embedded from the start.
Smart testing combines physical and virtual tests to build confidence faster:
• Simulation helps define realistic loading profiles for accelerated fatigue tests
• Physical tests provide data to improve simulation accuracy
• Uncertainty Quantification and probabilistic analysis help validate fatigue predictions
• Combining both methods gives more confidence than small-sample physical tests alone
Advanced reliability modelling, such as System-of-Systems simulation, helps engineers understand how multiple failure modes affect large systems—such as battery packs with many connected components. This supports better maintenance planning and helps meet goals for reliability, availability, maintainability, and sustainability.

2. Operation Space: After deployment, systems must be monitored and maintained. This space focuses on:
• Capturing real-world stress using operational data lakes, including the use of Physicsinformed Machine Learning to extract meaningful insights
• Measuring in-service strength using FRACAS (Failure Reporting, Analysis, and Corrective Action System) and maintenance records, with Machine Learning techniques to explore failure metrics more effectively
By linking design models with operational and maintenance data, engineers can build Digital Twins and Digital Passports. These virtual tools evolve with the product and create a feedback loop between design intent and field performance.

3. Design Feedback: The feedback loop from operation to design is becoming more dynamic. Technologies like Software-Defined Vehicles (SDVs) and Human–Machine Interfaces (HMIs) introduce new reliability challenges across hardware, software, and human-in-the-loop systems. We explore how vehicle simulators are used to capture these complex interactions and support a zero-prototype ambition for future development.
AI-powered reliability analysis can use historical FRACAS data to improve future FMEA processes.
This helps engineers predict problems and improve designs before production. The combination of data, simulation, and AI is changing how we learn from the field and apply those lessons to next-generation technologies.
This keynote aims to inspire new thinking about fatigue and reliability. It encourages academics and engineers to adopt digital tools and systems thinking to design sustainable, long-lasting technologies for tomorrow's world.

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FATIGUE DESIGN 2025

FD25-160

Advances in understanding cyclic crack initiation mechanisms in f.c.c. alloys: influence of plastic strain localization and hydrogen

Achraf Radi[1,2,3,4], Marion Risbet[2], Abdelali Oudriss[3], Gilbert Hénaff[4], Xavier Feaugas[3]

[1]Cetim, Senlis, France. [2]UTC, Laboratoire Roberval, Compiègne, France. [3]Laboratoire des Sciences de l'Ingénieur pour l'Environnement LaSIE, La Rochelle Université UMR-CNRS 7356, La Rochelle, France. [4]Institut Pprime ENSMA, Futuroscope, France

Even if it's already an old problem, the slip localization induced during a plastic deformation remains a complex subject associated with numerous elementary plasticity processes, the nature and the distribution of dislocations and the state of internal stresses. It is now established that this localization of deformation determines the initiation of surface damage in direct relation to the environment impact. In this sense, hydrogen as oxygen can be seen as one potential determining factor in the processes leading to this damage. Whether it is intrinsic and/or extrinsic, the hydrogen interacts with elasticity and plasticity properties contributing to profound changes in the processes of nucleation and multiplication of defects (vacancies, dislocations…). The distribution of these defects (dislocation structure, slip localization, vacancies clusters, …) and the associated internal stresses are directly affected and modified the condition of crack nucleation.

The goal of this talk is to summarize what is currently known about intra-granular crack initiation under cyclic loading in f.c.c. alloys, and to point out the new challenges that future studies should address. We revisit the implications of elementary plasticity, dislocation structures, and the associated internal stresses, after recalling the fundamental concepts of shielding, defactants, and hydrogen-enhanced vacancy clusters. Then we examine the role of hydrogen in the slip localization process to gain insight into the initiation of intra-granular damage. Crack initiation conditions near cyclic slip bands, associated with local plastic strain irreversibility, are established through atomic force microscopy measurements of surface topography evolution and transmission electron microscopy characterization of deformation localization, for nickel-based alloys exhibiting a wide range of grain sizes, precipitate sizes, and hydrogen contents. The local slip irreversibility, $\gamma_{irr,pl,loc}$, required for crack initiation has been expressed in terms of surface energy, the elastic energy stored by mobile dislocations, the applied stress amplitude, the dislocation mean free path, the hardening rate, and the elastic properties. It is concluded that the influence of hydrogen on $\gamma_{irr,pl,loc}$ is multifactorial.

S01
Additive Manufacturing

Chairmen:

Christophe Reynaud & Thomas Landro

Reynaud Christophe & Thomas Schmidt

Christophe Grosjean & Abdellaoui Benaouda

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FATIGUE DESIGN 2025

FD25-15

Fatigue performance of a titanium component produced by laser powder bed fusion

Kalle Lipiäinen[1], Mika Vaskelainen[2], Tero Pesonen[1], Masoud Moshtaghi[1]

[1]LUT University, Lappeenranta, Finland. [2]Patria, Tampere, Finland

Design based on an existing component geometry as a part of a structure was conducted. The design was manufactured using the laser powder bed fusion (L-PBF) technique. The reliability and consistent quality of AM materials are important aspects of the critical components manufacturing and verification process. Consequently, the same design was built with two different L-PBF setups for experimental studies. The effect of shop peening was studied as a potential fatigue performance improvement method. Experimental fatigue testing for the AM titanium component was conducted. The experimental study also includes surface quality and metallurgical analysis. Fatigue testing was supplemented with SEM fractography. The AM part exceeded design requirements for maximum service load significantly. The results highlight the potential of AM for component manufacturing in both new designs and replacing conventionally manufactured parts.

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FATIGUE DESIGN 2025

FD25-27

Fatigue assessment and simulations of steel produced using wire arc directed energy deposition

Elyas Ghafoori[1], Niels Pichler[2], Cheng Huang[3], Lingzhen Li[4], Leroy Gardner[3]

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[3]Imperial College London, London, United Kingdom. [4]ETH Zürich, Zurich, Switzerland

This work presents the behavior of as-built and machined wire arc additively manufactured (WAAM) steel. Using 3D laser scans of WAAM coupons, finite element (FE) models are developed and validated against experimental results obtained through digital image correlation (DIC). Methods for local stress analysis, accounting for material thickness, predict local stresses with reasonable accuracy and high computational efficiency. These stresses are then used to predict fatigue crack initiation and fatigue life, showing good agreement with experimental results classes, FAT 145 and FAT 135, with endurance limits of 270 MPa and 250 MPa, respectively, are derived for WAAM ER70S-6 steel using the proposed models.

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FATIGUE DESIGN 2025

FD25-53

Fatigue Performance Study of 316L Stainless Steel Specimens Fabricated by Selective Laser Melting

Yi Zhou, Ninian Sing Kok Ho, John Hock Lye Pang

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, Singapore

Fatigue design performance is an important factor for the industrial application of selective laser melting (SLM) technology. The SLM process is known to generate surface and internal defects, induced by material phase change during fabrication, which can lead to variability in fatigue performance of as-built, near-net-shaped specimens and parts. This paper investigates the fatigue behavior of as-built, machined, hot isostatic pressed (HIP) and shot peened specimens to assess the effects of these post-processing methods on fatigue life outcomes. SLM process vertically built 316L fatigue test specimens, in accordance with ASTM E466 hour-glass flat specimen geometry, were tested in the as-built condition, and the specimens were post-processed by machining, HIP treatment, and shot peening. The test results identified that the SLM fabricated materials exhibited improved fatigue properties through surface smoothing after the shot peening, resulting in a fatigue life increase of up to 65% compared to those that only underwent the HIP process. We also confirmed that in over 90% of the test specimens, the fatigue fracture occurred from the crack that initiated and propagated at the edges of the rectangular gauge section, which also supports the viewpoint that the surface defects act as weak points under the cyclic loadings. The findings primarily suggest that enhancing the fatigue properties of the additive manufacturing processed metal structures should focus on removing surface defects and improving the surface roughness, post-processing the surface condition of the fatigue test specimens.

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FATIGUE DESIGN 2025

FD25-56

Evaluation of high-cycle fatigue properties of additively manufactured SS316L via self-heating method

Mahmoud Barati[1], Behnaz Amini[2], Shabnam Arbab Chirani[2], Mahmoud Kadkhodaei[3], Mohsen Badrossamay[4]

[1]EMITECH Group, Montigny-le-Bretonneux, France. [2]ENIB, Brest, France.
[3]German International University, Berlin, Germany.
[4]Isfahan University of technology, Isfahan, Islamic Republic of Iran

Selective laser melting (SLM) as an Additive Manufacturing (AM) method has been recently used for the successful fabrication of metal components. Although additive manufacturing provides a flexibility in fabrication of complex geometries, this process might affect properties of the material such as mechanical fatigue life. The traditional methods for fatigue characterization are extremely time consuming and costly. Therefore, the self-heating test, as an alternative fatigue characterization method, is used. This method is based on the assessment of the material temperature variations occurred upon cyclic loading at various stress amplitudes. The principle of a self-heating test protocol consists of submitting a sample to successive series of cyclic loadings (or loading blocks), with a constant stress ratio and increasing stress amplitude, and recording the evolution of the temperature for each sequence. The results obtained from this method was justified for a wide range of conventionally manufactured metallic materials. In this study, the high-cycle fatigue behavior of additively manufactured Stainless Steel 316L (SS316L) by SLM is investigated with the use of a self-heating approach. During cyclic loading, mechanical irreversibility such as microplasticity and fatigue damage occurs, and the corresponding intrinsic dissipated energy leads to a heat generation, called material self-heating. By considering the same origin for the fatigue damage and the one that generates the heat dissipation, self-heating approach can be used to predict the fatigue properties of the material. With the use of self-heating approach, the fatigue limit for the additively manufactured SS316L samples are evaluated. A particular attention has been paid to the identification of the dissipative mechanisms responsible for the self-heating phenomenon. To this aim, different microscopic observation techniques have been conducted: optical microscopy, Scanning Electron Microscopy (SEM) and Electron Back Scatter Diffraction (EBSD) measurements have been carried out on the surface of specimen after cyclic loading. These observations show that several Persistent Slip Bands (PSBs) emerge, in a random way, at the specimen surface and the number of PSBs increases during cyclic loading. The emergence of PSBs at the surface is linked to the slip systems activation in the grain. The accumulation of microplasticity within these PSB structures leads to the fatigue micro-cracks initiation. Furthermore, for better comprehension, a two-scale model describing the probabilistic apparition of micro-plastic inclusions in an elastoplastic matrix is developed. It permits to reproduce self-heating results and then, by choosing an adapted fatigue criterion, is able to predict fatigue properties of the samples.

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FATIGUE DESIGN 2025

FD25-74

Dominant Microstructural Factors Contributing to Inferior Fatigue Resistance in Additively Manufactured Ni-Based Superalloy 718

Sungcheol Park[1], Yuya Tanaka[1,2], Saburo Okazaki[3], Yusuke Funakoshi[4], Hideto Kawashima[4], Hisao Matsunaga[1,5]

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Additive manufacturing (AM) has garnered attention as a promising production method for Ni-based superalloy 718 (Alloy 718) components with complex geometries. Despite the considerable potential of AM technology, challenges continue to hinder its widespread adoption. Two prominent issues are the small defects and complex microstructural characteristics induced by the AM process, both of which complicate the evaluation of fatigue strength. While many studies have focused on the impact of defects on the fatigue strength of AM alloys, systematic investigations linking microstructural features to fatigue behavior, particularly near the small fatigue-crack threshold regime, remain limited.

In this study, fully-reversed push-pull and torsional fatigue tests were conducted on AM Alloy 718 specimens. To isolate the effects of defects and microstructural characteristics, the fatigue limit was evaluated based on the shear-mode fatigue threshold, with quantitative consideration of the effect of defects. The results revealed that AM material exhibited inferior fatigue resistance compared to wrought (WR) material, regardless of defect size. Against this background, the microstructural factors contributing to the inferior fatigue crack-growth resistance of the AM alloy were comprehensively discussed.

First, the effects of precipitates (i.e., hardening precipitates, δ phases, and Laves phases), grain size, and residual stress were investigated. Additional fully-reversed push-pull fatigue tests were performed on another AM material with a different microstructure. The two AM materials differed in build rate (BR) and the presence of hot isostatic pressing (HIP). The original material was produced at a higher BR without HIP, while the new one was built at a lower BR with HIP. The lower BR and HIP process resulted in a fine grained, homogenized microstructure with likely negligible residual stresses in the new material. Nevertheless, the test results indicated that the shear-mode fatigue threshold of the new AM material was nearly equivalent to that of the original, suggesting that the influence of precipitates, grain size, and residual stress was minimal.

Second, the influence of crystallographic texture and annealing twin boundaries was examined in terms of grain misorientation. Specifically, the distribution of the twist angle between two adjacent crack planes at grain boundaries was analyzed along the crack path of both AM and WR alloys using electron backscatter diffraction and stereographic projection. It was concluded that the twist angle showed a strong correlation with the difference in shear-mode thresholds between these materials, identifying it as a possible dominant factor affecting small fatigue crack-growth resistance.

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FD25-86

Fatigue behavior of Aluminum DED material joined to a plate in load carrying and non-load carrying configurations

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Directed energy deposition with electric arc (DED-arc) can be used to manufacture components with high deposition rate. Furthermore, the productivity can be increased by utilizing DED material and components together with conventional plates and profiles. In this study, DED-arc parts and components made of aluminum material are studied. First, experimental fatigue tests are conducted for DED coupons. The material testing is followed by joining DED-produced coupon to plate with gas metal arc welding (GMAW) as butt joint configuration. The butt-welded joints are subjected to fatigue loading and the results are compared to plain DED material. The final part of the experimental testing widens the scope of the study to component level. The component-like specimen is manufactured in two possible manners. Oval shape thin-walled DED part is connected to a base plate that is loaded. The first case is to deposit the DED oval feature directly on top of the plate. The second case is to use platter to manufacture several DED oval features and then connect the DED part to the plate by fillet weld. In both cases, the global geometry is kept similar, whereas the residual stress state varies. Fatigue test results of the DED material, butt weld joint and component-like specimens are then discussed considering local properties.

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Characterization of Defects in Components Produced by Wire-Laser Additive Manufacturing Applied to Low-Alloy Steel

Rémi Thuillet, Imade Koutiri, Pierre Margerit, Fréderic Coste, Nicolas Ranc

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The wire laser additive manufacturing (WLAM) process enables the production of large-scale components. Therefore, it is essential to understand the fatigue behavior at high and very high number of cycles, as well as the scale effects and the mechanisms of fatigue crack propagation in parts produced by this process. Part of this study involves in-situ multimodal instrumentation of the process and a parametric analysis to establish the link between manufacturing parameters and the presence of defects (such as porosity and lack of fusion). The second part of the study consists of a fatigue testing campaign, both conventional (at 20 Hz) and ultrasonic (at 20 kHz), on samples with varying elemental volumes, ranging from a single layer to multiple layers, to better understand the scale and frequency effects on low-alloy steels produced via additive manufacturing (WLAM). The overall objective of these two parts is to establish a link between the fatigue behavior at a very high number of cycles and the parameters of the WLAM process.

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Numerical investigation of the effect of defect population on the fatigue strength anisotropy of Ti64 fabricated by Laser Powder Bed Fusion

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Defects induced by the fabrication process, which are dependent on the input process parameters, remain a critical issue in the fatigue design of industrial components processed by Laser Powder Bed Fusion (L-PBF). The present work aims to use numerical simulations to assess the impact of typical L-PBF defects on the High Cycle Fatigue strength of a high-strength material. To do so, real defect geometries have been explicitly integrated in the simulations, using X-ray tomography observations of different defect populations of Ti64 alloy processed by L-PBF. The fatigue strengths of the different defects have then been determined numerically for different types of loadings (tension, torsion, and tension-torsion) by applying the Crossland multiaxial fatigue criterion. A non-local analysis of the calculated stress fields was also included in the calculation of the Fatigue Indicator Parameter in order to account for the severe stress gradients at the vicinity of defects [F. Morel et al., International Journal of Fatigue, 2009; A. Karolczuk et al., Computational Materials Science, 2008; Y. Nadot & T. Billaudeau, Engineering Fracture Mechanics, 2006]. With this approach and by considering different loading directions, the fatigue strength anisotropy was assessed for two defect populations (gas pores and LoF defects) for the considered loading types.

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FD25-135

Influence of defect position on crack propagation in LBPF IN718

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The large possibilities of design offered by additive manufacturing (AM) has motivated numerous studies for process optimization. AM is particularly interesting for parts with complex shapes and for high-strength materials such as superalloys, which are difficult to machine. However, AM processes are prone to specific processing defects, such as gas porosity and lack of fusion. These defects are detrimental for components bearing fatigue loading because they constitute potential crack initiation sites. In order to investigate the effect of defect location on crack propagation in IN718, fatigue test specimens with artificial defects were processed by laser powder bed fusion (LPBF). Internal defects were introduced directly during material deposition, while surface defects were machined by electro discharge machining (EDM). High cycle fatigue (HCF) tests were carried out at both room temperature and 550 °C. Crack growth was monitored through potential drop technique, tomography for internal defects and high-resolution surface imaging for surface cracks. For both types of artificial defects, fatigue striations were also counted after fracture to get the local fatigue crack growth rate (FCGR). The associated stress intensity factor amplitude ΔK were calculated using the Z-Cracks module in Z-Set.

In the case of the surface defect, a strong plasticity effect was observed near the surface as well as a short crack effect. At room temperature, a lower FCGR is observed for internal defects. This indicates that, the defect atmosphere (air for surface defects, argon with traces of oxygen for internal defects) influences the FCGR in LPBF IN718. The same methodology was used at 550°C, showing in this case a stronger effect of the atmosphere. Indeed, for surface defects, the crack propagation is assisted by the oxidation of the material.

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FD25-139

Surface and Bulk Defects Influence in Fatigue of Additively Manufactured Ti-6Al-4V Alloys: a Unified Approach for Design Purposes

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Material inhomogeneities that occur across multiple length scales frequently impact metallic materials manufactured by additive methodologies. Both geometrical irregularities and non-metallic inclusions — often referred to as defects — can markedly degrade the fatigue performance of the manufactured material, particularly if no further post-processing is applied. As such, incorporating these defects into analyses is critical for an accurate evaluation of the material's structural integrity.

Fracture Mechanics-based approaches have proven effective in addressing bulk and sub-surface defects; however, a consensus has yet to be reached on the most effective method for addressing surface geometrical inhomogeneities (e.g., surface roughness).

This talk presents the effectiveness of a generalised defect-based model capable of accounting for bulk, sub-surface, and surface roughness effects. The model was calibrated based on a detailed experimental fatigue characterisation study of a Ti-6Al-4V alloy manufactured through two different techniques, i.e., Electron Beam Melting (EBM) and Selective Laser Melting (SLM). To achieve varied defect characteristics and quantitatively assess their influence on fatigue, the additively manufactured materials were subjected to different combinations of post-processing (e.g., Hot Isostatic Pressing, in-vacuum Heat Treatment).

This methodology proved effective across all examined material conditions, enabling a probabilistic evaluation of fatigue failure performance.

S02

Big Data and Artificial Intelligence

Chairmen:

Xavier hermite & Driss el khoukhi

Philippe Amuzuga & Denis Chojnacki

Philippe Amuzuga & Thomas Schmidt

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FD25-7

Machine Learning Metamodeling for Fatigue Life Estimation of Welded T-Joints

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Welded assemblies are commonly used in various industrial sectors. They constitute a versatile solution, notably due to their ability to withstand static and dynamic loads and temperature variations, all at reasonable costs. Their design and sizing are often governed by construction guides and standards to meet safety requirements, ensuring the integrity and durability of metallic structures. Fillet welds, commonly found in T-joints, are among the most common types.

Fatigue represents the most frequent failure mode in welded assemblies. Designing these joints to resist fatigue is a major challenge, as the lifespan of the entire structure is reduced to that of the weld when it represents the most critical area.

The evaluation and validation of the fatigue resistance of welded assemblies are not new and date back to the earliest industrial applications. Current methodologies, both analytical and numerical, aim for reliable accuracy to lighten structures without oversizing them, although they are often costly and time-consuming due to the need to adopt sophisticated techniques integrating specialized software. This study presents the application of Machine Learning to the metamodeling of a complete finite element analysis process by automating modeling, simulation, and fatigue analysis to estimate the fatigue life of T-welded joints, considering geometric parameters, loading conditions, and weld quality classes. Comparing the effects of configuration and data preprocessing of the training data set for several regression estimators led to a reduced model providing explicit empirical rules for design and fatigue life evaluation. Our results demonstrate the potential of artificial intelligence in mechanical engineering practices.

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FD25-9

Fatigue Assessment of Welded Joints using Extreme Value Statistics and Laser- Based Weld Toe Geometry Analysis

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This paper presents a novel approach for fatigue assessment of welded joints by employing extreme value statistics to predict the most critical weld toe geometry in welded structures. The methodology integrates advanced laser line sensor technology for precise weld geometry measurements, allowing the identification of geometrical features that are most likely to contribute to fatigue failure. By applying extreme value statistical techniques, the approach emphasizes the criticality of localized weld toe imperfections, providing a more accurate prediction of fatigue life compared to traditional methods. This technique offers improved reliability in fatigue life estimation for large welded structures, particularly in high-stress applications, and enhances the safety and durability of engineering designs.

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FD25-51

Predicting Fatigue Crack-Growth in Low-Alloy Steels Using Data and Image Analysis in Hydrogen Environments

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As the world advances towards decarbonization, hydrogen has emerged as a promising alternative to fossil fuels in various applications. However, the high cost of materials used in hydrogen production, storage, and transportation remains a significant barrier to widespread adoption. Such expensive materials are primarily employed to counteract a phenomenon known as hydrogen embrittlement (HE), which is often responsible for degrading the strength properties of materials storing it, leading to limited storage capacity and safety issues. Meanwhile, low-alloy steels are considered good candidates as the base material for their storing capacity at a moderate cost. Unfortunately, low-alloy steels are also subjected to hydrogen embrittlement.

The material's fatigue crack growth (FCG) rate is an important parameter considered during design. When comparing the FCG rate in hydrogen and air environments, low-alloy steels of tensile strength higher than 900 MPa display a significant acceleration of FCG rate, rapidly increasing along with the tensile strength. For application, fatigue testing in a hydrogen environment on materials considered is required, which is costly and time-consuming. However, predicting the FCG rate prior to testing would allow for more efficient and targeted testing, saving significant time and budget for laboratories.

In this study, we aim to predict materials' FCG rate in air and hydrogen environments from their heat treatment conditions and mechanical properties to identify optimal low-alloy steels with their associated process protocol in a minimum number of experiments. In addition to data analysis, image analysis using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) is integrated to enhance the prediction accuracy. Convolutional Neural Networks (CNNs) are employed for image analysis, while Random Forest is used for data interpretation. Further image analysis is also conducted independently to identify microstructural patterns and generate heatmaps, providing deeper insights into the FCG resistance of low-alloy steels in hydrogen environments.

This research aims to improve the comprehension of hydrogen embrittlement on low-alloy steels by bridging the gap between material science and machine learning. By integrating these two fields, we aim to create new high-strength materials that are compatible with high-pressure hydrogen environments, opening up new possibilities and potential in the field of materials engineering.

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FD25-57

Evaluation of the Influence of Weld Surface Seam Geometry on Fatigue Strength Prediction using a Data-driven Fatigue Assessment Method

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Fatigue design is crucial for reliable and lightweight steel structures. Especially, welded joints reduce the fatigue strength of those structures. This is attributed to the notched weld surface geometry and other phenomena like residual stresses or increased hardness value which are related to the welding process. It is well known that the weld surface geometry varies along the weld seam and due to that also the stress concentration. Measuring techniques like 3D laser scanning offer the possibility to capture these precisely and holistically along the weld seam. However, most commonly the nominal stress approach is used for fatigue strength assessment, which only considers the weld seam surface geometry globally. High safety margins are therefore required to ensure reliability, which on the other hand means that the full potential of lightweight construction cannot be fully exploited. Numerical methods based on the FEM can be used for a much more accurate fatigue strength assessment, but are computationally time-consuming and therefore practically not applicable for a holistic assessment of the weld seam. One possibility to overcome the lack of complexity of the nominal stress approach and the high computing times of FEM, is by using data driven methods based on Machine Learning (ML) algorithms. The success of data driven methods depends on the quality and the representation of the data.

This study employs ML to predict fatigue strength based on XGBoost models pretrained on flux cord arc welded (FCAW) and submerged arc welded (SAW) butt welds. Extending the dataset to include Laser Hybrid (LH) welds and specimens with weld imperfections, the research explores ML model transferability across different welding methods and imperfection types defined by ISO standards. Results highlight challenges in predicting fatigue life accurately when weld surface geometry varies or significant imperfections are present, emphasizing the need for robust anomaly detection in 3D laser scanning data. The study points out the impact of locally occurring weld defects and imperfections on fatigue life predictions and highlights the limitations of current data driven fatigue assessment methods. Based on this, it is discussed how the representation of the data is influenced by the use of different measures of location for the statistical distribution of weld surface geometry parameters.

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FD25-60

Principle strategies for the fatigue assessment of steels based on machine learning approaches

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Machine learning (ML) approaches gain more and more importance for fatigue assessment of materials and industrial parts. In this work an extensive database of more than 22.000 single fatigue test and 1100 fatigue test series (SN-curves) of different steels are used to build a generalized approach for the fatigue prediction based on machine learning. For this, different strategies are used: First, on SN-curve level, the fatigue life assessment based on SN-curves, where the SN-curve parameters (slope, fatigue strength) were determined by ML and used for the fatigue life prediction later; and second, the fatigue life prediction based on specimens, where the characteristics of single specimen of the fatigue tests series (stress amplitude, roughness, hardness, …) are used (specimen level). Different ML approaches like an artificial neural network (ANN) or random forest approach are used. A higher accuracy of the direct fatigue life prediction is shown. Slightly higher accuracy was determined using an ANN. This work shows the limitation using mainly commercial, older data sources for ML-based fatigue assessment with a certain degree of inconsistency that affect the prediction accuracy of this approaches.

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FD25-65

Machine learning model for estimating the stress concentration factor based on 3D scans of notched round bar specimens

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This work investigates the use of machine learning to predict the elastic stress concentration factor based on 3D scans of 135° V-notched round bar specimens. Traditionally, fatigue assessment of notched components relies on theoretical values. However, is highly dependent on the actual notch geometry, which can deviate significantly from the idealized geometry. These deviations impact the severity of the notch stress concentration and, consequently, the fatigue lifetime of a component. Therefore, fatigue assessment based on real notch geometries is of great interest.

The experimental work involved detailed 3D scanning of V-notched S690 steel specimens using a Keyence VR-5200 profilometer. These measurements were crucial for developing 151 finite element models, incorporating the actual notch profile data. In addition, the influence of specimen manufacturing on the experimental fatigue life was investigated by conducting rotating bending fatigue experiments on both polished and non-polished specimens.

The scans of the V-notched specimens were post-processed to create three-dimensional solid finite element models. For each of these finite element models, the corresponding -value was determined. These results served as the training database for the machine learning models. The input to the machine learning models is post-processed geometrical data derived from the 3D scans and the target variable is the corresponding -value determined with finite element analysis.

Various machine learning models were evaluated, with gradient boosting regression demonstrating the highest performance, achieving a mean absolute error of 0.039 and a coefficient of determination of 0.909 using features selected through recursive feature elimination. Careful preprocessing, resampling and data augmentation were critical for developing high-performance models. A case study highlighted the benefit of using profile data over discrete geometrical notch parameters when evaluating the stress concentration factor.

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FD25-71

Enhanced Understanding of Overhead Crane Fatigue Loading Using a Digital Twin Approach

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Overhead cranes are critical installations in industrial environments, especially in steel plants where they are subjected to significant cyclic loads and stresses. Traditional inspection methods provide only periodic snapshots of a crane's condition, leading to potential oversights and late-stage damage detection. This paper presents results obtained by a Structural Health Monitoring (SHM) system that leverages a digital twin approach to continuously evaluate the condition of overhead cranes.

The SHM system combines data from strain sensors and operational data with a numerical model of the crane. The system calculates fatigue life consumption based on EN 13001 and identifies critical areas requiring inspections, thus preventing costly failures and extending the crane's service life.

In this study the SHM digital twin approach is illustrated using results obtained from a 12.5-ton single box girder crane. The loading histogram of the crane is accurately measured. Next to that, the strain data is used to calculate the dynamic load factor for hoisting, accelerating and braking of the crane and the trolley. Data is presented of a dataset with measured crane operation events. The obtained results are compared with values considered in crane design methods. With actual measured data, the fatigue damage can be more accurately calculated and remaining lifetime can be assessed with increased confidence.

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FD25-84

Processing of point clouds from 3D scans of welded joints for the weld detection and weld quality analysis as input for a reliable fatigue assessment

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3D laser scans are increasingly used for the analysis of the weld quality. Based on these scans, it is possible to determine the weld profiles relevant for the fatigue strength, i.e. the weld angle and notch radii or other features as spatter or undercuts. These methods are currently developed and demonstrated in scientific investigations. However, in order to enable the applicability of 3D laser scans for quality assessment in practice, methods are still needed to automatically and reliably identify the weld seam and the weld direction from 3D scans. With these information, the weld profile in 2D cross-sections can be evaluated.

Current studies have shown that the detection of the weld seam is the major challenge for weld quality assessment based on local geometrical parameters (weld angle and notch radii). In this paper, different algorithms are presented that enable an automated weld seam detection. On the one hand, these are algorithm-based methods that are based on curvature of the surface, on the random sample consensus (RANSCAC) algorithm or artificial neural (ANN) networks are considered. All methods are presented in detail and applied as well as verified on a larger number of different weld geometries. A particular focus is placed on curved seams, i.e. welds on pipe joints, pipe flange connections or wrap-around welds.

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FD25-128

Defect generation based on micro-computed X-ray tomography and generative neural network: application to cast aluminium and additively stainless steel

Laurent Dolle[1], Pierre Merot[2], Franck Morel[2], Pierre Derian[1], Thomas Landron[3]

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In metallic alloys, inherent defects can significantly reduce resistance to high cycle fatigue, making them more vulnerable to failure. Several approaches exist to account for the effects of these defects, including methods based on Linear Elastic Fracture Mechanics (LEFM) or the use of fatigue criteria. Although these approaches are generally robust, accurately determining the defect population remains a challenge. A common non-destructive method for this is X-ray micro-computed tomography (µCT), which provides detailed information about defect distributions throughout the entire volume of the material. However, the use of µCT can be time-consuming, particularly for large volumes, and controlling thick samples is challenging due to X-ray attenuation. The present study investigates whether generative neural networks, such as diffusion models or GANs, can be used to build representative defect populations. This approach is applied to materials manufactured either by casting or by additive manufacturing: cast AlSi7Mg aluminium alloy and Laser Powder Bed Fused 316L steel. Generative neural networks are trained on µCT data from both materials, and the generated defect populations are analyzed for representativity. Finally, we discuss the relevance of the generated populations and suggest perspectives to enhance the robustness of this approach.The aim here is to build synthetic microstructure for fatigue predictions purpose.

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FATIGUE DESIGN 2025

FD25-157

Stress Concentration Factor Modelling from Weld Geometry Data for Fatigue Design

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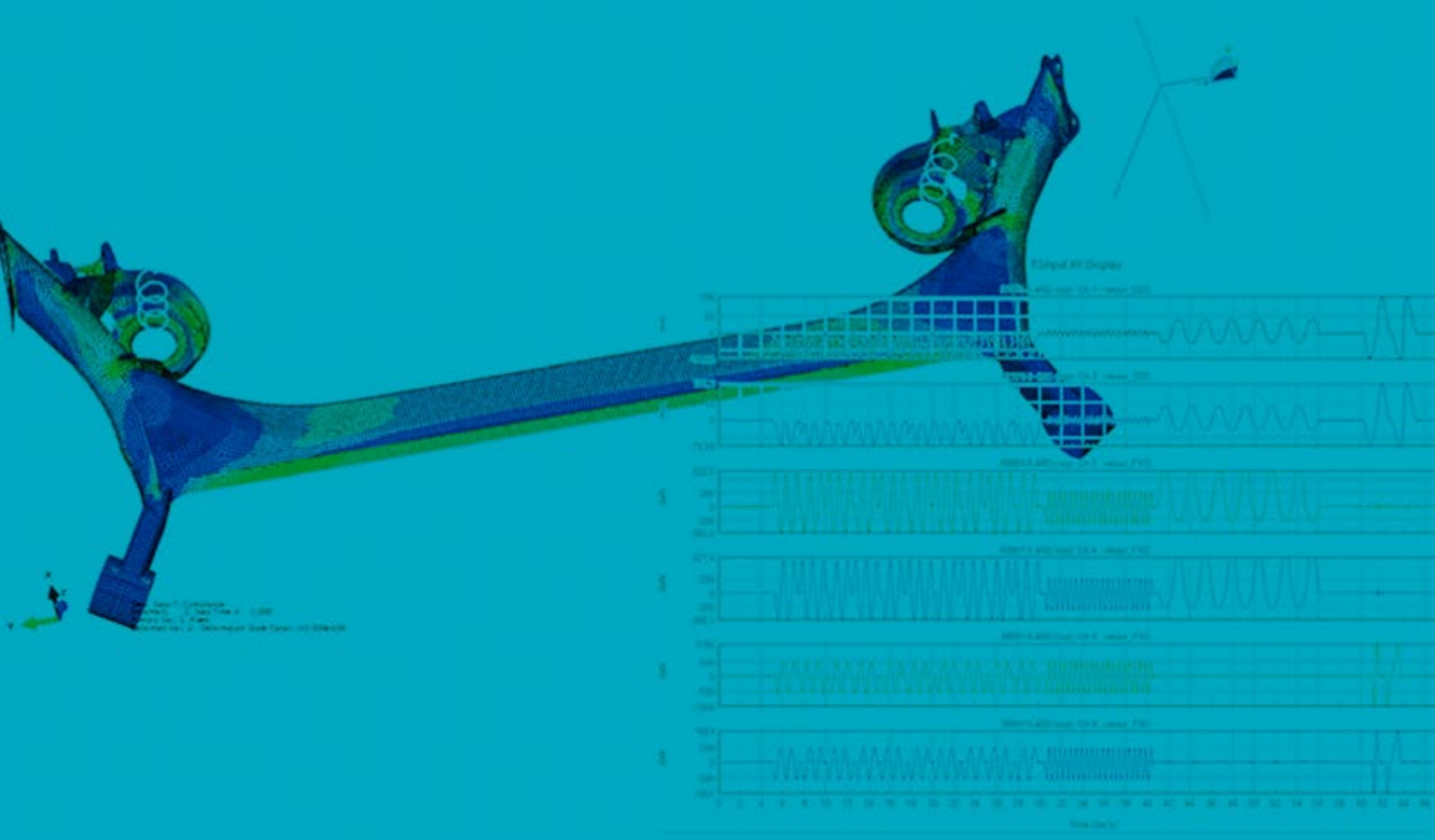
Welding is a widely used industrial process and a subject of extensive research, particularly regarding stress concentration caused by weld geometry. Although several models have been developed to estimate the service life of welded assemblies, their predictions often suffer from significant uncertainty, resulting in a wide dispersion of fatigue life estimates.

This paper presents an experimental methodology aimed at building a representative dataset of welds, for which multiple geometric features are measured, including 3D scanning. These measurements enable the evaluation of stress concentration factors through finite element analysis along the full length of each weld. A regression analysis is then performed on the collected data to derive an explicit model capable of estimating the stress concentration factor with acceptable accuracy based solely on weld geometry.

S03
Complex Loadings

Chairmen:

Mohamed Bennebach & Pierre Osmond



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FATIGUE DESIGN 2025

FD25-34

Determination of adequate reference mission for reliable fatigue design using Machine Learning algorithms

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The complexity of service loads on industrial structures, such as agricultural machinery, arises from both the variability of real-world missions and their multidimensional nature. Additionally, the reliability of individual metallic components (frame, suspension, transmission, couplers, etc.) must be ensured despite the diversity of local assemblies and associated failure modes. Reference loads used in these validation processes are typically derived from industrial knowledge of service conditions. However, industrial constraints limit the scope of measurable and distributable variables, the duration of measurement campaigns, and, consequently, the amount of data available for analysis.

In current paradigms, equivalent load theory is employed to maximize the utility of available data, as demonstrated by [Thomas 1998] and formalized by [Raoult 2020]. A key advantage of equivalent load approaches is that they simplify the specification of test loads for validating the reliability requirements of new projects. The nature of these test loads can vary, ranging from simple sinusoidal loads (as used in Wöhler curves) and theoretical Gaussian loading spectra (as in Gassner curves) to realistic loads derived from ad-hoc measurements, such as standard missions containing a representative number of severe events (schedules) or load ranges (spectra) [Berger 2002].

In this paper, we provide insights into developing a fatigue-motivated description of mission profiles by correlating them with realistic reference loads through equivalent load approaches. By applying a data augmentation process followed by dimensionality reduction via Principal Component Analysis (PCA) [Baroux 2022], we propose a simplified multidimensional representation of damage-inducing loads. The severities of specific usage scenarios are then simulated and distributed across various missions to determine an appropriate reference signal, ensuring a conservative validation of the project's reliability.

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FD25-49

Optimized specifications from mission profile campaigns and data management tool

Denis Chojnacki[1], Amaury Chabod[2], Sébastien Boudevin[3]

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The progressive electrification of many types of machinery (offroad, construction machines, etc.) is already engaged, whether for environmental requirements reasons, standards or efficiency. This transformation is most often achieved through the selection of components intended for a different primary use in terms of products (e.g. automotive). This on-going electrification leads to changes in technology, structure, design and final user behavior. In contrast with existing technologies, where standards may give guidelines, electric powertrain and its integration in complete new products requires new specification inputs. This raises a number of potential issues, such as the durability/safety of these components in another environment (e.g. telescopic handlers, excavators) and the overall product energy efficiency. As a result, customer usage in different life situations may result in a massive production of measurements. These variations must be finely understood with a dedicated infrastructure, which merges data storage, indexation and ability to achieve request with a good agility, and raw signals analysis tools, to calculate metrics. The Big Data environment enables to merge a variety of data, provide automatized analysis, up to a request-based dynamic dashboard.

Manufacturers therefore need to :

- Ensure that their component original specifications are in accordance with their product usage
- Optimize global operating efficiency (energy consumption, component performance).

The purpose of this paper is to explain the Mission Profile approach implemented by Cetim on demonstrators with a dedicated instrumentation (80 parameters). The post-processing activity is intended to create adapted specifications, indexed and classified by life situation. Indeed, the battery pack and electrical motors have to be optimized in real condition, and the test and simulation engineer needs to be aware of powertrain status, power and energy consumption in every condition. This approach, combined with the life situation from Big Data information, enables to create optimized specifications and to improve global energy performance.

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FATIGUE DESIGN 2025

FD25-108

Load modeling for chassis system fatigue design

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The design of chassis system components must meet strict durability criteria, ensuring compatibility with certain automative safety levels. In terms of fatigue strength, Stellantis ensures that all components can withstand a certain level of severity, reflecting every life situation encountered.

This severity level guides the measurement of loads during measures on proving grounds or with virtual road load. Then, these times histories serve as a reference for the validation of life durability of chassis system components. However, these reference loads are complex to handle and difficult to implement on test benches.

An initial solution was developed to simplify these complex loads by translating them into iso-damaging sinusoidal loads with constant amplitude. It has the advantage of handling basic load cases that are easier to implement. Howerver they remain uniaxial, based on specific assumptions about material fatigue behavior, and depend on parameters associated with the chosen behavior model. Consequently, this approach may be not reliable in certain configurations.

To overcome these limitations, a new solution has been developed: the use of a load spectrum model. This model reflects the complexity of the load by taking into account the number of occurrences for each level of load amplitude constituting a cycle.

However, implementing a load spectrum on a test bench requires defining the number of load blocks to be considered for the representation. Unlike the first method, multiple amplitude levels are taken into account. Therefore, it is essential to propose a robust method for defining the number of blocks and their characteristics, ensuring equivalent damage regardless of the fatigue behavior (Basquin model with one or two slopes) and the parameters of the considered load spectra model.

Moreover, due to the non-linearity of loads, the spectrum measured at the wheels may vary when studying local stress response. It is then necessary to define the conditions under which this non-linearity does not invalidate the proposed approach.

Finally, this work serves an overall goal: translating complex loads measured at the wheels to accurately observe local stress responses at any critical points of the chassis system. The aim is to define a set of load blocks that will validate the fatigue strengh of any critical point during bench test. This set must account for the varying fatigue behavior and must remain unaffected by the non-linearities in the loads measured at the considered critical point.

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Cruciform specimen design and manufacture for multidirectional carbon fiber reinforced composites subjected to biaxial tension-tension fatigue test

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Current specimen designs for biaxial tension-tension fatigue tests of composites are immature and often generate unexpected failure in fatigue tests, due to the lack of a design standard and the complexity of composite materials and multiaxial loads. So, designing composite structures with uniaxial testing is not sufficient due to the multiaxiality of the stress tensor. In this case, this paper aims to present an optimized specimen for multidirectional carbon fiber reinforced composites in biaxial tension-tension fatigue tests that fits with infrared thermography monitoring and provides a feasible specimen design by FE (Finite Element) simulation. Firstly, a design criterion is proposed to ensure a failure in the gauge region, a practical manufacturing approach, and optimal conditions for temperature measurement. An initial simulation model is established to find out the proper basic geometry followed by a more comprehensive simulation used for determining the dimension of the specimen. Consequently, the optimized specimen is designated as a cruciform shape with a reduced gauge region. Last, two stacking sequences of specimens, referred to as cross-ply [(0/90)6]s and quasi-isotropic [(0/45/90/-45)3]s, are tested in a simulation model that takes into account biaxial static and fatigue loadings, and then a few fatigue tests will be performed to validate the geometry. The favorable simulation and experimental results indicate the optimized specimen and design approach is well-suited for composite material in biaxial fatigue tests with temperature monitoring.

S04
Composite and Elastomers

Chairmen

Denis Espinassou & Abdellaoui Benaoud

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Mechanical behavior and damage analysis of discontinuous-reinforced composites under dynamic post-fatigue loading

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Up until this point, automotive structures have been designed based on mechanical characterizations carried out on materials that have not been subjected to any stress. However, the majority of automotive structures are subjected to fatigue-type stresses prior to a crash. It is therefore essential to assess the residual properties of materials that have undergone partial fatigue-type loading under rapid loading conditions. The question that this study seeks to answer is as follows: This study aims to investigate the impact of fatigue-type loading on the residual dynamic behavior of composite materials with discontinuous reinforcements. The objective of this paper is to examine the impact of fatigue-induced pre-damage on the dynamic tensile behavior of discontinuous-reinforced Advanced Sheet Molding Compounds (A-SMC). This study establishes a foundation for the topic by comparing the post-fatigue dynamic properties with those of the corresponding virgin material. Tension-tension fatigue preloads at a frequency of 30 Hz are conducted at varying levels of applied stress. Subsequently, the samples underwent tensile testing at varying strain rates, specifically 10^{-3} s^{-1} (quasi-static), 1 s^{-1} and 100 s^{-1}. It has been demonstrated that the overall quasi-static and dynamic responses are significantly influenced by the number of fatigue cycles accumulated prior to the imposition of the high strain rate load. Furthermore, the impact of pre-fatigue damage is also significantly influenced by the strain rate. The experimental results demonstrate that the damage threshold in terms of stress and strain increases with the strain rate. However, for a given strain rate, the damage threshold depends on the number of cycles applied during the fatigue preload. The results of this study, which provide valuable insights into the underlying phenomena, particularly damage, form an essential experimental basis. This is crucial for the development of new dimensioning tools tailored to structures under cyclic and dynamic loading.

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FD25-141

Deep learning simulations of self-heating using physics-informed neural networks: determination of fatigue limits for laminated composites

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The main objective of this study is to simulate the fatigue limits properties of a high-strength unidirectional carbon/epoxy ply. The focus is on reconstructing the fatigue characteristics of a carbon/epoxy elementary ply using advanced approaches based on Physics-Informed Neural Networks. In this context, artificial neural networks were developed to represent experimental data while incorporating heat transfert models that describe the self-heating phenomenon in laminated composite materials under cyclic loading.

Classical fatigue tests were used to construct Wöhler curves, which represent the relationship between the number of cycles to failure and the applied load amplitude. These curves provide a comprehensive view of the performance of laminated composite materials under different loading regimes. In parallel, the fatigue limits determined from self-heating tests were compared with those obtained from classical tests. The results show a strong correlation between the two methods, validating the self-heating-based approach as a fast and effective alternative for evaluating the durability of composites.

Identifying the fatigue limits and parameters of a PINN involves training the neural network on a dataset to represent all experimental data within the identification domain. In the case of PINNs associated with experimental data, an inverse analysis is performed to determine the neural network and the parameters corresponding to the solution of the differential equation or partial differential equation derived from physics. In our case, this is the heat equation and, consequently, the conduction properties of the laminated specimen. After optimizing the model parameters and those of the neural network, the network will reproduce the experimental data and provide approximations outside the identified points. Unlike traditional numerical methods such as finite element analysis, the domain is not meshed. These neural networks, known as Physics-Informed Neural Networks (PINNs), stand out for their ability to integrate physical laws into the learning process, thereby ensuring greater accuracy and enhanced robustness of predictions. Various composite laminates were tested to better understand the influence of laminated architecture on fatigue behavior and fatigue limits.

In conclusion, the self-heating method is a valuable tool for engineers and researchers seeking to quickly assess the fatigue performance of materials while saving time and resources. Moreover, the use of physics-informed neural networks represents a significant advancement in the field of modeling and predicting fatigue behavior, enabling a reduction in the number of experimental tests required and accelerating the design and validation processes for composite structures.

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FD25-158

Towards new approaches for estimating the fatigue limit of Polymer-Matrix Composites (PMCs) under the self-heating tests

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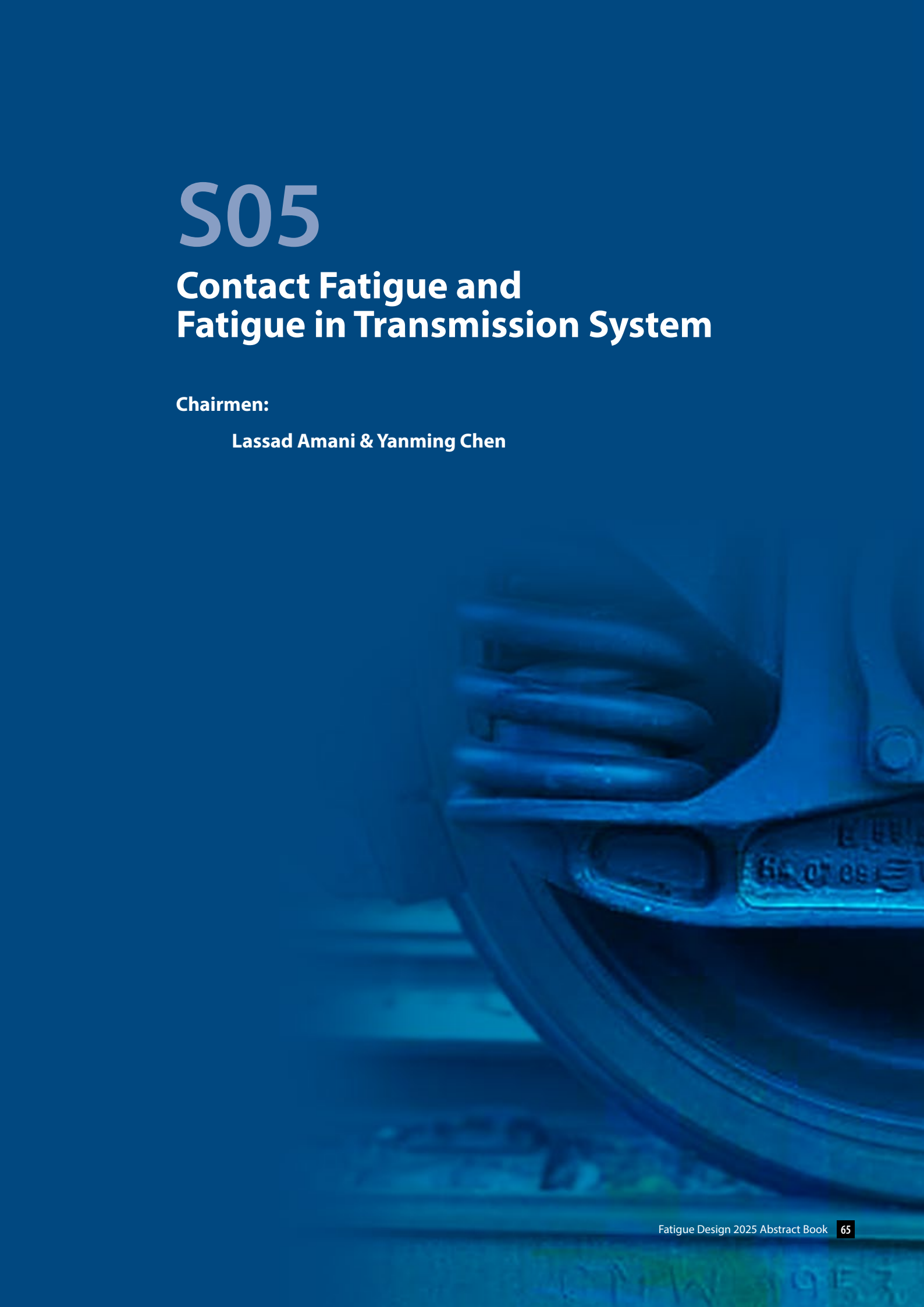
Beyond the stabilized temperature traditionally analyzed in self-heating tests, this study introduces two innovative parameters for estimating the fatigue limit of polymer matrix composites (PMCs): the electrical capacitance of an embedded piezoelectric transducer and the piezoresistive response of PMCs reinforced with conductive carbon fibers—both explored here for the first time, to our knowledge. To further ensure an objective and automated determination of the fatigue limit, we propose a novel approach termed the "elbow method." Applied to both temperature and capacitance data, each stabilized in blocks, this method produces highly consistent and reliable results when compared with the conventional Luong method.

S05

Contact Fatigue and Fatigue in Transmission System

Chairmen:

Lassad Amani & Yanming Chen



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FD25-29

Non-Destructive Thermographic approach for a rapid fatigue limit estimation of gears

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Gear resistance is an important mechanical aspect to ensure the proper functioning of power transmission systems. In general, gear design is based on both geometry and material parameters and, in many cases, surface treatments are required to guarantee the desired mechanical properties. It is well known that one of the most dangerous failures in gears refers to tooth root fillet cracks, caused by bending fatigue. In general, mechanical parameters involved in fatigue resistance for materials or components, such as bending fatigue limit, are evaluated by means of dedicated experimental campaigns. Standards help engineers in the gear design phase by providing material resistance data arranged on the basis of chemical composition, manufacturing process and surface treatment. This approach requires significant time and effort from the experimental point of view to obtain limited and unlimited life curves (S-N diagram), which are essential for the evaluation of the bending fatigue resistance of the gear under consideration. Regarding the experimental campaigns, bending fatigue tests may be performed following two classical approaches, Meshing Gears (MG) and Single Tooth Bending Fatigue (STBF) tests. In this work, the STBF approach was adopted in combination with a Thermographic monitoring. This way, a full superficial acquisition of the tooth root thermal emission was performed during the fatigue test at different loads. So, the fatigue limit was estimated from an iterative analysis of thermal parameters evolution (Two Curves Method, TCM). The proposed Non-Destructive Thermographic approach (TCM), already well-established in the literature for classical samples, allowed in this work to obtain fatigue limit data in the specific case of gears. Gears made of C45 and 20MnCr5 with surface treatments as induction hardening and case hardening respectively were tested. The obtained results in terms of bending fatigue limit values were compared with those evaluated by using consolidated approaches as the Stair Case Method and with the indications available in ISO 6336 Standard for that material.

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FD25-30

Application of self-heating method for characterization of 42CrMo4+QT steel under fretting fatigue conditions

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This paper presents fretting fatigue tests on 42CrMo4+QT steel, combined with self-heating measurements. The thermal imaging technique was used for rapid evaluation of the fretting fatigue limit targeting minimal consumption of test samples. Tests with load asymmetry ratios of R = -1 and R = 0 were performed using two different fretting pad geometries. The resulting fatigue limits were compared with values obtained from conventional fretting fatigue S-N curves. Elastic-plastic simulations of the experiments were conducted, and multiaxial fatigue criteria were applied to assess the risk of crack initiation. Additionally, a qualitative assessment was made to predict crack initiation locations according to observations from fractography.

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FD25-47

The influence of shot peening on gear teeth micropitting – Complementary analyses

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Micropitting damage, commonly seen in case-hardened gears, gradually deteriorates the contact surface geometries, potentially leading to macropitting and fatigue failure. A previous Cetim study based on gear contact fatigue tests investigated the effect of shot peening on the micropitting and its development to macropitting on case-hardened gears. A specific shot peening is employed to optimize the surface roughness of the flanks. Initial inspection of gear specimens revealed that shot peening resulted in higher surface residual stresses and lower surface roughness compared to ground tooth flanks (without shot peening). Experimental results showed that while both specimens exhibited micropitting, it was more pronounced on the shot-peened tooth flanks, with greater tooth profile loss. However, it was found that shot peening delayed the onset of macropitting, extending the gear's durability by more than 50%.

This work seeks to explore why shot-peened gears, despite exhibiting higher surface residual stresses and reduced surface roughness, deteriorate more quickly. Analyses were carried out, including surface damage assessments using microscopy and interferometric profiles, and damage mechanism analysis through EBSD technique. Results showed micropitting craters of 10-100 µm in size and 1-5 µm in depth, with significant crystallinity reduction in worn areas. Tribological tests were also conducted on tribometer according to ASTM G-133 in crossed cylinder/cylinder mode to measure the friction coefficient. These tests allowed the reproduction of micropitting on the non-peened surface of cylinder extracted from gear after 20 000 cycles, while no micropitting was observed on a shot-peened surface even after 340 000 cycles.

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Calculation of the bending fatigue strength of shot peened gears in the VHCF range

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Shot peening is applied more frequently to enhance the tooth root load carrying capacity of gears. As a result of this process, increased compressive residual stresses are incorporated into the material's surface layer, leading to a significant rise in the tooth root load carrying capacity. An additional requirement of modern powertrains is also the endurance of load cycles into the VHCF range, especially for electrified powertrains and other applications like trains or the power generation sector, e.g. wind turbines. More recent studies have shown that, especially in the VHCF range, shot-peened gears tend to have a crack initiation at a non-metallic inclusion with the formation of a so-called fisheye beneath the surface, which leads to a decrease in the tooth root load carrying capacity. This circumstance is not yet considered in widely used calculation methods such as ISO 6336 for gears, mainly due to limited experimental results for gears tested in the VHCF range. Therefore, this paper presents extensive experimental results regarding tooth root failures in the VHCF range. Four different material batches of three different steel grades are being investigated. The experimental results were obtained by pulsator tests and gear running tests on the FZG back-to-back test rig. Based on the experimental results, a calculation model is derived to consider the weakening effect of non-metallic inclusions on the tooth root load carrying capacity in the VHCF range. Finally, recommendations are given on how the effects could be regarded in standards such as ISO 6336.

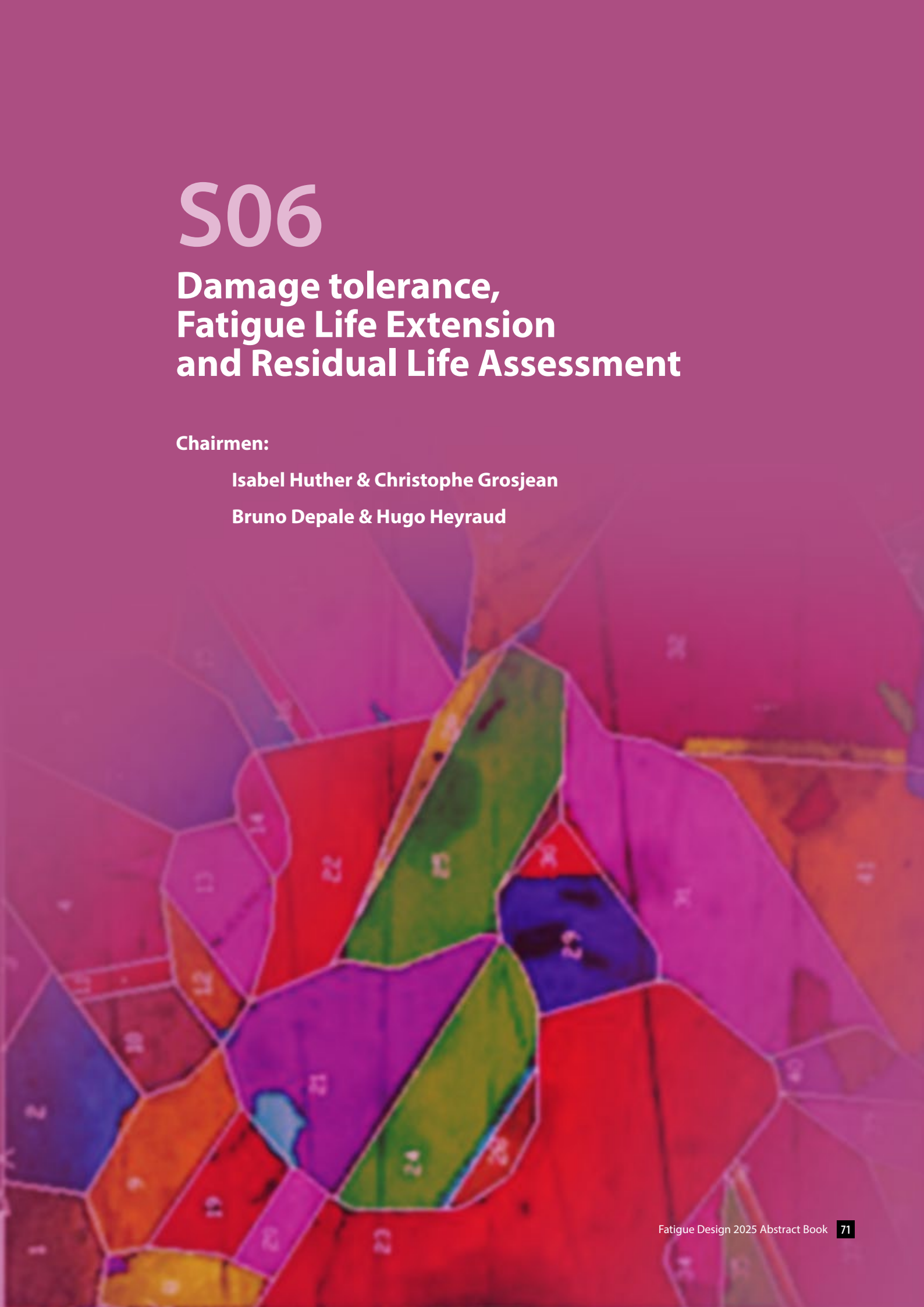
S06

Damage tolerance, Fatigue Life Extension and Residual Life Assessment

Chairmen:

Isabel Huther & Christophe Grosjean

Bruno Depale & Hugo Heyraud



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FATIGUE DESIGN 2025

FD25-8

Non-local continuum damage mechanics-based crack growth modelling for high- performing steel structures

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Efficient utilization of high-strength steel is crucial in various industrial applications, including offshore structures, ships, and bridges. To achieve this, advanced manufacturing and analytical tools are required to consider the fatigue strength of high-performing surfaces and welded joints. In high-performing structures, the reduction in imperfection size results in higher fatigue strength than conventional ones, especially when high-strength steel is used. Therefore, fatigue modelling of the initiation and propagation of short cracks is essential for evaluating high-performing structures. In this context, non-local continuum damage mechanics-based modelling of crack initiation and growth has gained attention lately. This model relies on local stress and strain fields and the accumulation of fatigue damage within representative volume element depending on grain size statistics for arbitrary shaped imperfections and various crack sizes. Thus, the method enables explicitly considering the effects of surface roughness, material mechanical properties, and residual stress. As a result, this model estimates fatigue life for all short crack initiation and short and long crack propagation, extending beyond fracture mechanics-based methods that require the assumption of initial crack size. This paper aims to present a methodology of continuum damage mechanics-based modelling and its application to the analysis of short crack initiation and growth in high-performing structures. The methodology provides a detailed description of the modelling concept, the procedures for calculating the fatigue life, and simulation tools using finite-element methods. The application cases include high-quality cut-edge plates and welded joints with superior fatigue strength. The results of estimated fatigue life are compared to experimental data. After that, this study discusses the fatigue damage mechanism of high-performing structures by focusing on the change of local fatigue response during short crack growth.

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FD25-26

Fatigue strengthening and lifetime extension of steel structures with bonded CFRP and SMA materials

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The International Energy Agency estimates that direct CO2 emissions due to crude steel production is approximately 1.4 tons CO2 per ton steel produced. In order to achieve the targets of Net Zero 2050, steel industry has to reduce the greenhouse gas emissions. An effective approach to reach this target is to practice repair or reuse of existing structures to reduce the demand for crude steel production. Application of shape memory alloys (SMAs) and carbon fibre-reinforced polymer (CFRP) materials has shown a great potential for lifetime extension of steel structures. In this work, the principle of fatigue strengthening using SMA and CFRP materials are discussed. Different prestressed bonded and unbonded systems are presented. Finally, a few different applications of fatigue lifetime extension of steel bridges are presented.

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FD25-61

A comprehensive review of Fatigue Crack Growth laws and models

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Fatigue is the most common cause of failure in structures subject to cyclic loading. Fatigue failure is a two-stage phenomenon consisting of a crack initiation stage followed by a propagation stage. Cracks can initiate due to fatigue but also as a result of manufacturing processes and material features such as inclusions or voids. Once a crack is present, if it is subject to a sufficiently high cyclic stress, it will propagate until failure. However, in some instances a crack can propagate into a low-stressed region causing the crack to stall and never propagate to failure. In this case the crack may be acceptable in-service as it might not compromise the durability of the component (damage tolerant approach).

Fatigue crack growth refers to the propagation (or non-propagation) of cracks in structures subject to cyclic loading. Fatigue crack growth and damage tolerant analyses use fracture mechanics principles and therefore, the knowledge of pre-existing cracks is necessary. These pre-existing cracks can be detected in components using non-destructive techniques or assumed.

From the second half of the 20th century, significant research effort was put in understanding and describing how cracks propagate under cyclic loading, including how to characterise the threshold, propagation and fast fracture regions, both from an experimental and numerical point of view, as well as how to account for mean stress effect and crack retardation. Unfortunately, this research effort is scattered in a multitude of scientific publications.

The purpose of this paper is to provide in a single document a comprehensive collection of the most relevant fatigue crack growth laws and models allowing a more effective review and comparison of the available tools and facilitating decision making.

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FD25-72

Influence of defects detected by penetrant testing on fatigue properties in cast material for marine propellers

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Products of the metal founding industry are manufactured in a single step from liquid metal without intermediate operation of mechanical working. The advantage of this process is the shaping of all types of pieces either tall, thick or with a complex geometry. However, they may contain several casting defects such as shrinkage defects due to the dendritic growth during solidification. Defects can have an influence on the fatigue limit of the material because of local stress concentration.

In the naval industry, before launching, big casting products like marine propellers pass a conformity check through penetrant testing. It is a non-destructive method that allows to reveal surface defects in order to determine critical defects through acceptance criteria based on norms and reference documents.

The objective of the study is to understand the acceptation criteria of defects in order to avoid rejects and numerous repairs on CuAl casting propellers. The step of the work are firstly to understand the fatigue behavior of the alloy in the presence of natural defects, then to analyze the reduction of the fatigue limit depending on the size of defects through a Kitagawa-Takahashi diagram. All of the fracture surfaces are analyzed to determine the origin of crack initiation. The final aim is to establish the link between fatigue and penetrant testing, as the results will be described with a Kitagawa-Takahashi / NDT diagram which shows the fatigue limit depending on the size of the penetrant testing indication.

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FD25-73

Investigation of Laser Shock Peening and Conventional Shot Peening on the Fatigue Crack Growth Rate of Aluminium 2024 T4 Alloy

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Typically, most of the aerospace and automotive components and mechanical structures are subjected to a cycling and/or fluctuating loads when in service. Hence, these structures are likely to fail due to fatigue if the applied cycling stress is at an adequate level to initiate and propagate the crack.

However, aluminium and its alloys are ideally used in industrial application because of its weight to strength ratio. Furthermore, aluminium alloys provide high resistance to corrosion and excellent fatigue resistance. Nevertheless, in some applications where an alternative load is applied over an intense and persistent number of cycles, the use of an aluminium alloy will be on the margin due to its fatigue strength. Therefore, in order to improve its fatigue lifetime, the aluminium alloy will be treated either by Laser Shock Peening (LSP) or by Conventional Shot Peening (CSP), both of which are forms of mechanical surface treatment.

This research will investigate the Laser Shock Peening (LSP) and Conventional Shot Peening (CSP) on the fatigue crack growth behaviour and the fatigue properties of the 2024-T4 aluminium alloy. This investigation focused on the role that the peening induced residual compressive stress, surface morphology and hardness on the crack growth rate and the fatigue life of the test specimens. Furthermore, a comparison of the induced residual compressive stress depth measurement between the two surface treatments (LSP and CSP) will be explored within this study.

Finally, from this research a recommendation for when and where each of the two surface treatments (LSP and CSP) could be implemented and how they will be beneficial for the structural integrity of the parts and/or components which have experienced the penning.

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FD25-81

Residual Life Assessment (RLA) of Long Bien Bridge (Hanoi)

Bruno Depale[1], Dinh Duc Pham[2], Danh Le Ba[2]

[1]Cetim, Senlis, France. [2]HUCE, Hanoi, Vietnam

Long Bien Bridge (LBB) built between 1899 and 1902, is the iconic bridge of Hanoi. The bridge's length is 2 290 meters across the Red River and, due to History, only some parts of the original structure remain intact, while large sections have been built later to repair the holes and destroyed parts.

To ensure the safety and durability of the bridge, it is necessary to have a complete diagnostic of the structure under various loadings, with a distribution of the stresses in the load-carrying components. This is why Cetim and HUCE modelled numerically the first six spans of LBB, on Hanoi city side, for simulating the mechanical behavior, supporting the existing plans for maintenance and being a guideline of the project for complete renovation of LBB. A campaign of geometric measurement was necessary to recalibrate the theoretical modelling based on drawings and the various degradations (loss of thickness due to corrosion, holes…) and modifications (repairs, replacement of structural components…) were also considered.

The final evaluation of RLA required the iterative analysis of the archives data collected concerning the different traffic histories of the bridge (trains, trucks, ...) to the relevant load cases and load combinations.

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FD25-92

Monitoring the Mechanical Environment Harshness and Assessing the Remaining Life of Sensitive Equipment

Jean-Yves Disson, Mohamed El Yazrhi

Metravib, Limonest, France

This paper introduces the works and the results performed for monitoring vibrations at the foot of sensitive equipment to evaluate the severity of mechanical environments and estimate the equipment's remaining lifespan. We have developed a prototype system that measures accelerations and calculates, in real time, the shock response spectra and fatigue damage spectra, which characterize shock and vibration-induced fatigue severities.

Despite the computational demands of these indicators, we successfully integrated them into a compact datalogger capable of real-time data acquisition and processing. Our study demonstrates the feasibility of continuously monitoring and analyzing vibrations throughout the equipment's lifecycle without human intervention. An embedded classifier further enhances the system by detecting different usage conditions, effectively identifying various life situations.

These capabilities provide two fundamental insights into the equipment's reliability:

- Reliability Assurance: Ensuring the equipment has not been subjected to mechanical stresses exceeding those it was qualified for during vibration table tests, both for shocks and cumulative fatigue from vibrations.
- Residual Lifetime Assessment: Evaluating the remaining operational lifespan of the equipment by considering its specific mission profile.

Finally, the processed data from the datalogger can be utilized to design new equipment subjected to similar mechanical environments, with a high confidence regarding the mechanical environment.

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FD25-143

A Novel Solid-State Recycling Approach for Submarine Hulls: Mechanical and Fatigue Characterization

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Conventional recycling of steel components through the fusion process leads to a degradation of mechanical properties, limiting the circularity rate. This study explores an alternative solidstate recycling approach applied to submarine hulls made of high-strength, high-thickness steel plates formed by rolling process. The approach leverages a thermomechanical process to flatten the hull structure and produce raw machining blanks.

The first part of this work focuses on optimizing the bending process and thermal treatment used to flatten the thick steel plates from decommissioned submarines. A life cycle analysis is performed to assess the new process's environmental footprint, revealing a significant reduction compared to conventional steel recycling, primarily due to the relatively low processing temperature and the absence of post-treatment operations.

The second part investigates the combined effects of decades of service history and the thermomechanical recycling treatment. The mechanical properties of the recycled material are compared to those of the original material in two aspects: (1) hardness and residual stress profiles and (2) mechanical and fatigue properties in different directions of the sheet plane. The results demonstrate that the recycled material retains mechanical properties comparable to the original steel, unlocking new high-value applications.

By preserving the original alloy composition and mitigating the drawbacks of melting, this innovative approach offers the potentiality to enhance material circularity, reduce CO_2 emissions, and increase both the economic value and mechanical performance of recycled steel. Extensions of this approach to other flat products, such as automotive bodywork or aircraft wings, will now be explored.

S07

Experimental and Numerical Design and Validation Methods

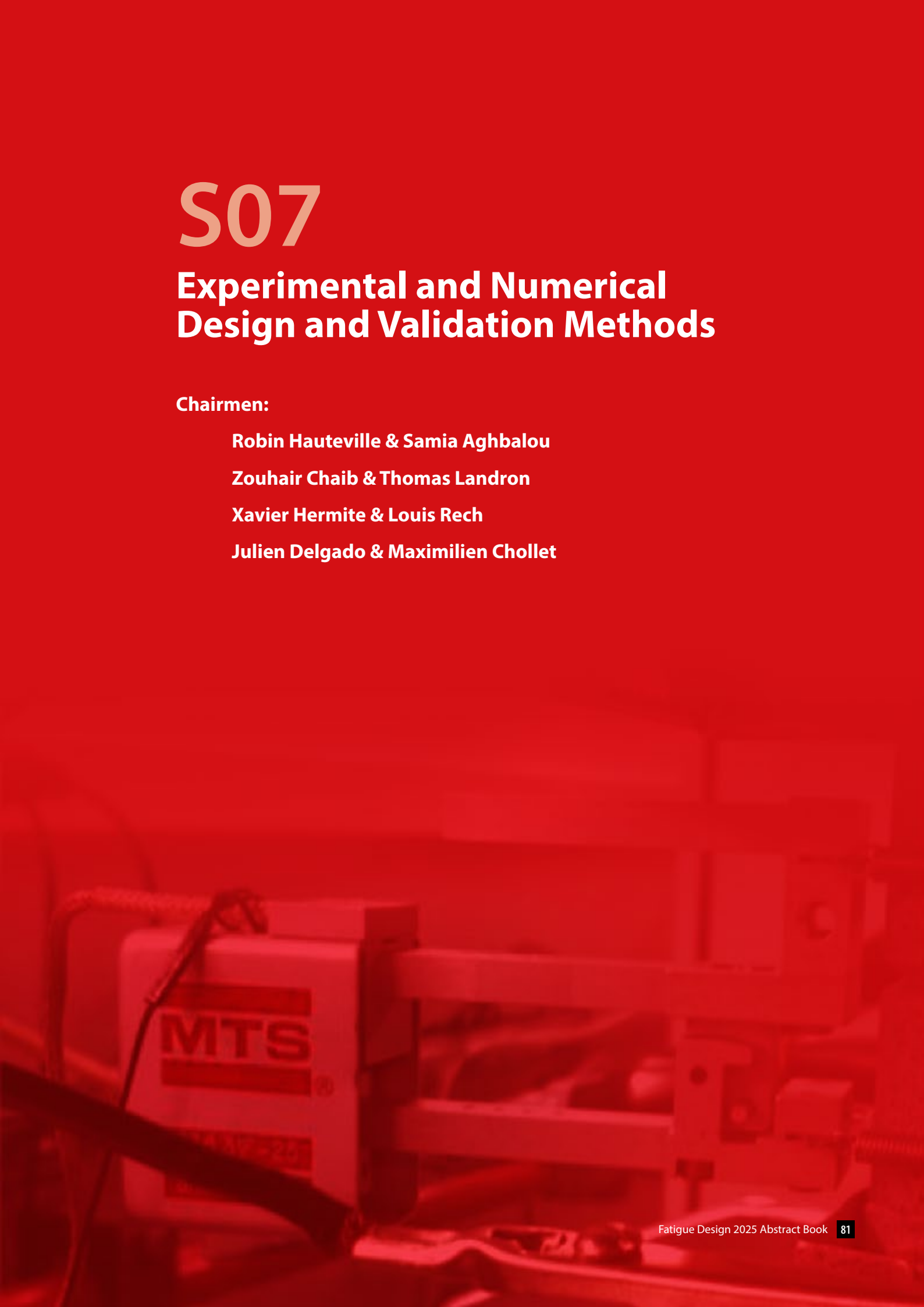
Chairmen:

Robin Hauteville & Samia Aghbalou

Zouhair Chaib & Thomas Landron

Xavier Hermite & Louis Rech

Julien Delgado & Maximilien Chollet



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FATIGUE DESIGN 2025

FD25-2

Experimental and numerical investigations on the fatigue behaviour of intermittent rail welds of crane runway beams

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Crane runway beams differ from other structural components used in conventional steel structures since they are subject to frequently recurring stresses due to the introduction of wheel loads from cranes. Crane runway beams that support top-running overhead bridge cranes are often made from hot-rolled I sections. In case of light crane service, a flat bar of structural steel is commonly used as crane rail and is attached to the upper flange of the beam's I section by fillet welds. The rail welds are exposed to multi-axial stresses resulting from the local wheel load introduction and the global bending and are, therefore, at risk of fatigue. At present, the current version of EN 1993-1-9:2005 contains neither a suitable detail category nor appropriate design rules for intermittent rail welds.

In an ongoing research project, the fatigue behaviour of intermittent rail welds is being investigated both numerically by means of finite element calculations and experimentally in fatigue tests under travelling wheel loads. Both chain and staggered intermittent rail welds are being investigated. The objective of this research project is to develop a generally valid and practicable proposal for the fatigue analysis of intermittent rail welds according to the nominal stress concept, that meets the reliability requirements set out in Eurocode.

This paper provides a brief overview of the ongoing research project and presents the first findings. The finite element model for determining the nominal stresses of rail welds, which was presented at the Fatigue Design 2023 conference, has been verified by means of tests on the contact conditions between the crane rail and the top flange of the crane runway beam. The verified model is used to investigate the effects of the wheel load eccentricity in the cross-section of the crane runway beam and the influence of the global shear stresses on the nominal stresses. Furthermore, the effective notch stresses of the rail welds are determined using the sub-modelling technique and compared with the nominal stresses in order to derive fatigue notch factors.

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FD25-22

Balancing Recovery Stress and Structural Fatigue Behavior in Iron-based Shape Memory Alloys: New Insights for Construction Applications

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One of the most important applications of Iron-based Shape Memory Alloys (Fe-SMA) in the construction sector is utilizing their recovery stress for pre-stressing structural elements such as concrete and metallic beams and plates, which are subsequently subjected to cyclic loads. This makes it crucial to develop a reliable fatigue design process for the attached Fe-SMA members.

It is known that the fatigue strength of metals decreases with an increase in the stress ratio (R). Since Fe-SMA members in civil engineering are used in a prestressed form, the mean stress level plays a significant role in determining the fatigue strength of the alloy. This is particularly important because the alloy is generally used as a prestressing element with superimposed cyclic service loads, resulting in large stress ratios, potentially up to R = 0.7.

Recent studies have shown the potential of tailoring Fe-SMA properties to achieve higher recovery stresses, reaching up to 600 MPa. On one hand, this results in higher potential pre-stress levels, but on the other hand, it also increases the stress ratio. While recent research has focused on enhancing the recovery stress of Fe-SMA pre-stressing members, the urgent need to assess the changing structural fatigue behavior has been somewhat neglected.

Therefore, this study aims to provide initial insights into this research gap by systematically analyzing the influence of different heat-treated conditions of Fe-SMA on their structural fatigue behavior. This analysis includes studying the impact of varying stress ratios due to tailored pre-stress levels (recovery stress) and different service load levels. This work will help establish a more comprehensive understanding of the fatigue behavior of Fe-SMA members, facilitating the development of safer and more reliable applications in the construction sector.

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FD25-28

Total Fatigue Life Testing of High Strength Steels and Conventional Structural Steels

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In recent years there has been a surge in production of high strength steel (HSS) due to market demand. Application of HSS has increased in the field of construction and heavy industrial equipment in order to optimize the product weight, with a focus on sustainability. An important feature is that HSS has higher yield strength than conventional structural steels, but lower ductility. Based on this, it is often assumed that HSS would perform better in terms of the fatigue strength. However, this assumption requires additional validation considering manufacturing and environmental effects, where higher ductility would be more beneficial. This paper discusses the comparative analysis of the total fatigue life assessment of different steel grades (from low to high) assuming crack initiation and crack propagation. The fatigue crack initiation tests are carried out using Shimadzu ultrasonic fatigue testing system USF-2000A. The fracture mechanics based fatigue crack propagation tests are carried out using servo-hydraulic testing machine Instron 8801. The influence of corrosion on fatigue life is also discussed, and the paper concludes with a comparison of the "total fatigue life" strength of HSS and conventional steels.

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FD25-33

Methodological Tools for Engineers: How to Assess the Relevance of Using a Uniaxial Fatigue Life Assessment With Eurocode 3 or Multiaxial Fatigue Life Assessment With a Dang Van-Type Criterion? Application to Mechanical Parts of Cableway Installations

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For an overall state of traction (hydrostatic pressure > 0), it is clearly established that determining the lifetime of a mechanical part subjected to multiaxial stress states via a uniaxial fatigue estimation method (such as EN 1993-1- 9) can lead to overestimating the lifetime of this part and therefore have a negative impact on safety. Carrying out a multiaxial fatigue calculation (Dang Van-type criterion) is therefore more realistic but more costly in terms of time and know-how than a uniaxial fatigue calculation (EN 1993-1-9 type). In practice, the safety components of cableways are subject to multiaxial stress state, but at what level of multiaxiality is it really necessary to carry out a multiaxial fatigue lifetime calculation? To help the engineer decide which method to apply: we offer a simple tool based on reading charts, to quickly determine depending on the parameters of bi-axiality of the signal (sigma_II/sigma_I ratio, average stress, variation of loading angle) the difference in lifetime between an estimation by Eurocode (NE) or by Dang Van (NDV). We then discuss acceptable NDV/NE lifetime variation values to be applied by the cableway sector profession for future standardisation work.

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FD25-44

On the determination of fracture properties of specimens subjected to periodic fatigue loadings using DIC

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In this work, some important concepts are covered in the context of measuring the fracture properties of specimens subjected to high frequency periodic fatigue loadings using Digital Image Correlation (DIC). For fatigue tests, depending on the selected cycle frequency, high-speed machine vision cameras are commonly employed. These cameras can be replaced by low-cost, high-resolution and limited-frame-rate machine-vision cameras. A signal-locking approach can be used in these applications to grab images at the loading peaks or artificially reconstruct the source signal using aliasing. With regard to the fracture properties, the stress intensity factors, crack-tip position and strain energy release rate can be measured using DIC. Here a fully integrated system is presented and validated using the Williams' series expansion model.

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FATIGUE DESIGN 2025

FD25-58

Fatigue strength assessment of large bolting assemblies using the notch-strain approach

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Due to trends such as increasing tower heights, optimizing the design of wind turbine towers with regard to their fatigue strength is becoming increasingly important. For this reason, all available fatigue strength potentials must be used. To be able to make use of existing fatigue strength potentials of bolting assemblies used for example in the tower flanges, the new revision of Eurocode 3 part 1-9 (prEN 1993-1-9:2023) considers more differentiated detail categories, taking into account size effects, the thread manufacturing process as well as the effect of zinc coatings. However, incorporating positive or negative influences on the fatigue strength beyond the scope of the specified detail categories is difficult, since the underlying nominal stress concept requires additional tests for any additional influencing parameter. This is a particular challenge for large bolting assemblies of nominal diameter d > M36, such as those used in current tower designs, as the experimental investigation of individual influencing parameters is costly and time-consuming.

Compared to this, the notch-strain approach allows for the differentiated consideration of individual influences based on the analytical or numerical calculation of local stresses and strains as well as on small-scale base material tests. In theory, changes in the bolt material, thread manufacturing process, bolt geometry, preload level, loading scenario and surface layer can be considered in one or more subsystems of the concept without the need for tests on the full-scale bolting assembly. However, the accuracy of the notch-strain approach heavily depends on the accuracy of the base material characterization as well as on the selected modelling approaches in the different subsystems of the concept and is still a subject of research.

In this context, an ongoing public funded research project regarding the influences on the fatigue strength of large bolting assemblies (d > M36) delivers extensive test results and offers a large database for the validation of corresponding calculations using the notch-strain approach. The methods for the implementation, the results of the validation as well as the conclusions for the further development of the notch-strain approach for application to large bolting assemblies are presented and discussed in this paper.

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FD25-63

Characterization and modeling of the impact of micro-shrinkage porosity on the high cycle fatigue resistance of cast G20Mn5 steel

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Shrinkage porosities are the main cause of fatigue crack initiation in cast steel components subjected to cyclic loads. Advanced foundry processes can eliminate large shrinkage pores by optimizing the component geometry, the mold and the feeding system. However, micro-shrinkage pores always remain present and their size is generally in the order of several hundreds of micrometers. The impact of these pores on the fatigue resistance has been extensively documented for cast aluminum alloys, but there is a lack of quantitative studies concerning cast steels.

The study aims at demonstrating how micro-shrinkage pores affect the fatigue resistance of the G20Mn5 cast steel under high-cycle fatigue (HCF) conditions for uniaxial and torsional loads. It investigates the size, position, geometry, and distribution of micro-shrinkage pore populations and examines three specimen configurations of cast G20Mn5 steel with varying micro-shrinkage pore sizes while maintaining a similar microstructure, determined by a normalization heat treatment after casting. An almost porosity-free material obtained using the HIP process is also studied as a reference material. HCF tests (censured at Nmax=107cycles) in tension-compression (R=-1) and torsional (R=-1) loading conditions were performed on cylindrical specimens. The fatigue failure surfaces of all the failed specimens were observed using scanning electron microscopy (SEM) to characterize the critical pore at the crack initiation site. The size, distance to the surface, and circularity were measured. 3D tomography tests were conducted on certain fatigue specimens before and after fatigue testing to assess the impact of the real micro-shrinkage distribution on the fatigue resistance. Additionally, fatigue specimens containing artificial defect will be loaded, in combination with triggered optical observations to measure the on-surface crack propagation rate.

The preliminary results indicates that for the configurations containing pores, fatigue cracks initiate at surface pores. While for the "pore-free" configuration, cracks typically initiate at inter-metallic inclusions. The study uses Kitagawa-Takahashi diagrams to examine how pore size affects the fatigue strength. Differences in the fatigue strength, between the uniaxial and torsional loading conditions are observed, with a less sensitivity to the pore size for pure shear loading mode. A statistical simulation based on X-ray tomography data and using a Kitagawa type model illustrates how the distribution of the micro-shrinkage pores affect the fatigue resistance.

This PhD project is a French CIFRE collaboration between Safe Metal and the LAMPA laboratory of the Arts and Métiers Institute of Technology.

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FD25-66

A Non-conventional Fracture Mechanics-based Multiaxial Fatigue Assessment of Defective and Sharply Notched Metallic Materials

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This work focuses on the prediction of the multiaxial fatigue limit at constant amplitude for metallic materials weakened by stress concentrators. Developing predictive models for multiaxial fatigue limits, which enable the analysis of the effects of defects and notches, is especially relevant in the context of the rapid advancement of Additive Manufacturing (AM) technologies. This is due to two main reasons: (i) current AM processes are inherently prone to defects, and (ii) AM technologies allow manufacturing components with complex geometries, such as lattice structures, characterized by the presence of notches and multiaxial stress states.

More specifically, the study addresses the engineering estimation of the multiaxial fatigue limit in the presence of defects, cracks, and sharp U or V notches and proposes a unified design criterion based on the Averaged Strain Energy Density (SED) approach, which extends the Atzori-Lazzarin-Meneghetti (ALM) diagram to multiaxial loadings. The SED framework offers a method to define both an equivalent defect-free material fatigue limit, denoted as $\Delta\sigma_{0eq}$, and an equivalent fatigue threshold, for any local stress field. By combining these two parameters using an El Haddad Smith Topper-type equation, defect sensitivity under local multiaxial stresses can be described.

An extensive validation against experimental multiaxial fatigue limits is included, demonstrating the sound correlation between theoretical estimations and experimental results. This validation highlights the robustness and reliability of the proposed method in view of real-world applications, where understanding the impact of stress raisers, such as defects and notches, is critical to ensure the structural integrity of mechanical components.

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FD25-91

A Study on Forward and Reverse Methods for the Evaluation of S-N curves

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The evaluation of S-N curves is a fundamental aspect of fatigue analysis in mechanical engineering. However, the reverse evaluation, defined as the minimization of the error term between the data and the S-N curve model in the direction of the unobserved variable "stress", represents an area that is still insufficiently addressed in the literature. Consequently, the forward evaluation is defined as the minimization of the error term in the direction of the observed variable "lifetime". This study systematically investigates both forward and reverse evaluations of S-N curves using Maximum Likelihood across different S-N curve models, including the linear and bi-linear Basquin models, as well as their corresponding statistical representations. A comprehensive analysis is performed to clarify the advantages, disadvantages and limitations of each approach in terms of convergence behavior and effective utilization of experimental data. Given the inherent challenges associated with fatigue testing, which often involves limited datasets and significant costs, it is crucial to optimize the use of available data. The results of this research are expected to improve the understanding of S-N curve evaluations, thereby increasing the accuracy and applicability of fatigue analysis methods.

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FATIGUE DESIGN 2025

FD25-95

Towards a better assessment of Clip-connector fatigue thanks to an improved design methodology and the use of acoustic emission

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Safe, efficient and reliable offshore drilling technologies are needed to enable the exploration of oil and gas fields in the challenging deep-water environment. This presents a real challenge for the drilling riser, whose static and dynamic behavior depends on numerous parameters related to operational and environmental conditions. Improved and more predictive design methodologies are required to better assess the margins of drilling riser couplings with respect to their static performance and fatigue life.

Fatigue life evaluation of drilling riser connectors is based, per API16F standard, on the material design S-N curve and the stress amplification factor calculated with the maximum alternating principal stress via linear elastic analysis. A series of fatigue tests carried out under cyclic tension loads on an actual Clip-Riser™ connector showed that this approach leads to overly conservative results.

This paper proposes a methodology to improve the prediction of Clip-connector fatigue life that takes into account material non-linearity and multiaxial stresses for the assessment of stress range and mean stress. Fatigue tests carried out on small-sized Clip-connector prototypes have validated this design methodology in terms of fatigue life assessment and fatigue crack initiation detection.

In order to determine as accurately as possible the fatigue damage threshold of Clip-connector prototypes at the various loading levels considered, the fatigue tests were instrumented using Acoustic Emission, in parallel with conventional instrumentation using strain gauges and extensometers.

This robust and recognized NDT technique enables real-time recording of acoustic waves generated by the metallic material under solicitation. Analysis of the specific characteristics of these mechanical waves generated by the assembly - and in particular the initiation and propagation of cracks at the hot spot - has enabled us to determine the AE damage threshold within the connector prototypes, consistent with the crack initiation determined by mechanical instrumentation.

An initial analysis was carried out by an Acoustic Emission expert, based on his experience and the variations in parameters recognized as influential, in connection with the appearance of damage in metal structures. In order to evaluate the transposition of this monitoring to a real industrial structure, for much longer acquisition times, a detection algorithm using Machine Learning was also set up and the results compared with "manual" expertise.

The combined use of enhanced design methodologies and fatigue testing with advanced NDT monitoring has led to a better understanding of the Clip-connector fatigue and improved prediction of their service life.

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FD25-101

Load effect, notch effect, size effect, and other related factors in the stress-based fatigue estimation is there a way to unite them?

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The field of fatigue stress-life estimation addresses the effects mentioned in the title differently. The load effect differentiates among various loading modes that lead to uneven stress distributions across the critical cross-section. The notch effect accounts for this uneven stress distribution when induced by structural irregularities. Conversely, the size effect – sometimes referred to as the "statistical" size effect – addresses the weak-link mechanism of fatigue damage, where larger components subjected to the maximum stress are more likely to initiate cracks if compared to smaller components with the same maximum stress. This effect may interact with both the load and notch effects.

The FKM Guideline identifies two additional effects to consider: (1) the mechanical deformation effect, which assesses the material's yielding capability, and (2) fracture mechanics effect, which slows crack propagation in the presence of stress gradients. The latter effect shares similarities with both the load and notch effects.

This paper proposes an attempt to unify the notch and size effects into a critical volume effect, relating to the size of the control volume directly influenced by stress distribution within the component. The evaluation is based on a test case involving six variants of specimens manufactured from a single batch of S355J2 structural steel. These variants include one unnotched hollow configuration and five notched configurations with varying notch acuities. The specimens are subject to load control through three different fatigue loading modes: push-pull, torsion and plane bending.

Based on experimental results, the critical volume solution is developed to address this issue. The paper discusses its current limitations and provides a comparison with typical stress-gradient solutions and with the application of the theory of critical distances.

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FD25-109

Fatigue life of wheels regarding design and test constraints

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Wheels both for passenger cars and trucks are one of the most safety critical parts on vehicles. Knowing this, in the 1970's automotive industry started to rethink the design and also the lifetime assessment of wheels with respect to their different use case scenarios. Detailed measurements revealed the load influences from on- and off-road usage also including special and extreme load events. At that time, the BiAx or ZWARP test technology for rotating components of wheel ends were developed using these real life measurements to achieve a realistic fatigue assessment for any kind of wheel or hub in a lab environment.

In the last years, the demands for the fatigue assessment have developed both with the variety of wheels and the usage itself. Especially, with regard to wheel and tire sizes as well as wheel test technology new demands from the customer side open up new research demands to assess the wheel's strength. To detect the influences of fatigue test methods, the wheel and also the tire size intense fatigue investigations at Fraunhofer LBF were conducted. The aim was to derive the significances influencing the fatigue result and the parameters driving the fatigue assessment of hubs and wheels. The investigations showed that e.g. the tire ratio has a significant influence on the local loads on the wheel and thus the fatigue strength. This needs to be taken into account for the lifetime assessment and the fatigue test procedure to ensure a safe and reliable product.

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FATIGUE DESIGN 2025

FD25-115

Evolving internal length scales during fatigue crack growth: Insights from statistical fractography and implications for fatigue design

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A comprehensive description of the failure of materials under cyclic loads is key for their safe operations. Experimental investigations have routinely represented fatigue failure through the S-N curve and the Paris' law. While in the first case, the failure of specimens results from the growth of microscopic cracks, the second case pertains to tracking the evolution of an existing macroscopic crack. A connection between these two curves has strategic value and yet is not clearly understood. As a result, insights from experiments of fatigue failure are mostly phenomenological. Moreover, with the sensitivity of fatigue life to mean stress, surface finish, etc., traditional safe-life design routinely involves prolonged experimental campaigns.

During this presentation, we will discuss how the statistical analysis of the roughness of fracture surfaces helps in simplifying, and ultimately shortening, conventional experimental protocols. Recently, statistical fractography has been successfully employed to measure the fracture toughness Kc of failed parts as well as their in-service loading. It relies on the measurements of characteristic length scales of damage processes (e.g. process zone size) from the statistical analysis of material's fracture surface.

When it comes to fatigue failure, we observe that such length scales are not constant. Instead, they increase as loading amplitude ΔK increases - an observation that is at odds with the constant size of the process zone considered in standard models. To investigate further this phenomenon, we study the displacement field in the vicinity of a fatigue crack-tip using digital image correlation (DIC). Our experiments carried on Al 7075 alloy reveal the presence of a non-elastic region near the crack tip emerging from the damage activity ahead of the crack. As the fatigue load amplitudes ΔK varies, the characteristic size of this zone varies too, and is found to be in good agreement with the fractography. The existence of a loading amplitude dependent length scale has interesting implications. Similar to the short-crack theory, it argues for a connection between the mechanism of fatigue involving the initiation of cracks and for the growth of existing cracks.

From an engineering perspective, these results pave the way for determining specimen exhaustive S-N curve reliably from a single fatigue crack growth experiment of high cycle fatigue. As a proof of concept, we determine the S-N curve from the fatigue experiment of the aluminum alloy. The implications of our work for a simpler characterization of the fatigue failure properties of components is finally discussed.

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FD25-124

Material mechanisms of the nanostructured metallic multilayer post-weld treatment for fatigue strength increase

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While traditional post weld treatments intend to reduce the fatigue failure potential by changing the weld seam geometry, introduction of compressive residual stresses and shielding of environmental impacts, the nanostructured metallic multilayer (NMM) covers all three mechanisms simultaneously. NMM offer combined high strength and ductility and significantly enhanced fatigue resistance.

In a recent study we detected a strong enhancement in fatigue resistance of the weld through applied NMM and a small scatter of results indicating a high reliability of the method. Through XRD testing at the P61A-beamline at the German Synchrotron (DESY) we understood that residual stresses, which are generated through the deposition process, play a major role in enhancing the fatigue resistance of the weld. Tensile stress in the nanolaminate causes beneficial compressive stress in the substrate which counteracts fatigue crack initiation resulting in an unmatched increase in fatigue strength. NMM treatment of the double V weld increases the fatigue strength from FAT class 80 to beyond 190. This paper investigates under which conditions and controlled by which parameters the tensile stress distribution in the nano multilayer is optimized, paving the way for NMM to reliably and economically contribute to longevity and reduced maintenance of cyclically loaded metal infrastructure.

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FATIGUE DESIGN 2025

FD25-154

An innovative simulation strategy for low-cycle fatigue design of a S355 welded assembly

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The weight reduction requirements of industrial vehicles force engineers to choose materials, geometries and manufacturing methods that lead to the most favorable strength/mass ratio. Consequently, fatigue resistance takes an important place in the dimensioning of structures in order to ensure a recommended service life. The quality of the predictions given by the usual fatigue criteria strongly depends on the precision with which the in-service stresses are calculated. For welded joints subjected to cyclic loads, the in-service stresses depend on the residual welding stresses and their evolution during the loading cycles. If the loading cycles lead to plasticization of the structure, the latter can then reach an elastic or elastoplastic stabilized state which can be linked to the behavior of the material itself or to certain combinations of primary and secondary loadings. This work relates to the study of a mechanical element in S355 steel belonging to the French brand Haulotte. The research carried out on this type of element is focused on articulation pivots, subjected to strong stresses. According the experimental observations, there is no doubt that fatigue-type problems on the weld seams are present. Thus the development of a multi-phasic numerical model made it possible to calculate a stabilized cyclic state as well as to estimate the life time in oligocyclic fatigue conditions. These results could be verified by comparing them to experimental tests carried out on real parts.

S08

Fatigue and Manufacturing Process

Chairmen:

Abdellaoui Benaouda & Guy Fournel

Victorien Gautheron & Xavier Hermite

Victorien Gautheron & Maximilien Chollet

Driss el khoukhi & Samia Aghbalou

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FD25-24

Fatigue Strength Improvement by Machining Process in Stainless Steel Welds

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The increased use of integral structures is critical for developing improved commercial transport structures and unmanned and manned space transport. They reduce the use of rivets and the need to create lap joints, the primary source location of multi-site fatigue damage, especially in airframe structures. One method being examined is to produce and join large modular units by welding. Welding is essential in the construction, aircraft, aerospace, and automotive industries. However, welded joints are sensitive to fatigue failure due to cyclic loading and fatigue crack propagation influenced by welding residual stresses (RS) distribution. Welding residual stresses are caused by differential thermal expansion and contraction of the weld metal and parent material. In and near the weld, residual stress levels can be very high, up to material yield strength magnitude in highly constrained situations, which is the case in most real structures. The residual stress in a welded joint can augment the externally applied load and cause structural failure. The fatigue life of the welding can be increased by machining the weld bead to reduce from higher to lower tensile residual stress, and compressive residual stresses in the weld bead are removed. This research analyzes the fatigue strength developed by a robotic welding process and subsequent machining of the weld bead through a control numerical process in duplex stainless steel 2205 (DSS). Two main variables will be studied: i) heat input as a welding variable and ii) chip cross-sectional area as a machining variable. Results showed that X-ray diffraction measurement along the center thickness of the machined welded plates reveals compressive residual stress near the adjacent weld region, and the fatigue life of the machined weldment are enhanced by 80% at a stress level of 550 MPa and 92% at 350 MPa compared to the DSS welds with the weld bead.

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Integrating machining conditions to calculate the fatigue life of a mechanical part

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This article deals with the optimization of the fatigue life of machined surfaces. Since 2005, the LTDS laboratory a has developed a scientific method to predict the residual stress state generated by cutting operations on surfaces. This so-called "hybrid" modeling principle is based on equivalent thermomechanical loadings calibrated with experimental machining forces. This model has reached a high level of technological and scientific maturity. So, starting with the turning process, this methodology is now available as a software called MISULAB that predicts the three-dimensional residual stress fields on any kind of turned parts. The aim of this article is to show how three-dimensional residual stress fields on machined surfaces can be used in fatigue strength calculations of a shaft. The article shows how MISULAB can be connected to the NCode DesignLife software and how it can be used to maximize the fatigue life of a rotating shaft by optimizing machining conditions.

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Fatigue life modeling of steel cords under complex loads

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A truck tire is a complex assembly of several composite plies composed of an elastomer matrix reinforced by steel cords. These cords consist of several thin, high-strength brass-coated steel wires assembled in a helix. Their primary function is to support the mechanical cyclic loading induced by the vehicle rolling, which leads to fatigue damage. However, during tire life, oxygen and water from the ambient environment can diffuse through the polymer matrix because its aging causes a change in its chemical properties, adding a combined corrosion effect to mechanical fatigue.

To reduce the global weight of a truck tire, the total mass of steel cords, which represents 25 % of the tire's mass, should be minimized, leading to higher stresses on the material. Still, this reduction can only be done by ensuring similar or better performances. Therefore, it is of primary importance to predict the fatigue behavior of steel cords under mechanical and chemical loadings. This study aims to develop a reliable model predicting the fatigue life of steel cords, which implies understanding fatigue and fatigue-corrosion mechanisms. Considering a multiscale approach, a pre-existing lifetime prediction model at the scale of a single wire has been enriched to consider the fatigue-corrosion mechanism of brass-coated steel wires, which is caused by a double galvanic coupling: dealloying of the brass and, due to a not fully covering coating, preferential corrosion of iron. This damage of fatigue corrosion was studied using an experimental setup that enabled electrochemical measurements to be carried out during a bending rotation test.

A lifetime prediction model at the scale of the steel cords was developed based on this single wire model. Stress states in each wire were obtained using finite element simulations of a cable surrounded with a rubber matrix and subjected to bending and tension-bending loadings. The damage of these wires was first considered independent from one another, and their fatigue lives were computed using the single wire model, enabling the computation of a probability of rupture. The lifetime results were compared to experimental fatigue lives of cables subjected to bending-tension cyclic loadings.

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Assessment of tensile and fatigue properties of lattice structure manufactured by laser powder bed fusion

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The design of heat exchangers produced through additive manufacturing presents a significant challenge in achieving the goal of net-zero carbon emissions in aviation by 2050. A key advantage of additive manufacturing is its ability to create complex structures that are not feasible using traditional methods. In this context, a collaborative project involving Sogeclair Aerospace, CEA, Addup, and ONERA was launched to develop an initial version of such a heat exchanger. ONERA's role is centred on characterising the material properties of laser-powder bed fused (LPBF) AlSi7Mg. The forthcoming heat exchanger includes large components, thin-walled tubes, and thin-walls, each of which may exhibit different mechanical properties due to the varying cooling rates inherent to additive manufacturing.

As a result, a lattice structure representative of the heat exchanger was designed and tested under both static and fatigue loading conditions. Fatigue testing was conducted at a frequency of 20 Hz with a stress ratio of 0.1. A staircase method was used at 105 cycles to estimate the corresponding local stress. Following the staircase, the full S-N curve was obtained by testing higher stress levels. Fractured samples were then examined under a scanning electron microscope to identify the critical features responsible for crack initiation. Additionally, a numerical finite element method model was developed to correlate the results. The corresponding geometric model was created based on the results from tomography, providing insight geometrical information of the lattice structure sample.

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Determination of fatigue effective notch stresses based on the real weld geometry considering effects of welding imperfections

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This work investigates the impact of the real weld geometry and geometric weld imperfections on the fatigue strength of butt welded joints. Numerical calculations of the fatigue test clamping process, based on the real weld geometry, are employed to quantify stress raising effects due to welding imperfections. In addition, stress concentration and fatigue notch factors are computed based on the theory of critical distance according to Peterson that takes into account the material micro-support effect. The real weld geometry is incorporated by using the reverse engineering process. For that, the real weld geometry has first been scanned and transformed into an equidistantly ordered point cloud. Using a self-developed algorithm, the point cloud has been inserted into a CAD model, which exhibited the same geometric welding imperfections, i.e., axial misalignment and angular distortion as the real specimen.

Additionally, this study examines the correlation between clamping-induced stresses and these geometric welding imperfections. The results indicate that clamping-induced stress increases with greater misalignments.

Furthermore, the fatigue strength of butt welded specimens made from S355MLO mild steel is comparatively investigated using the established fatigue assessment methods nominal stress approach and the conventional notch stress approach, based on the numerically computed fatigue notch factors and fatigue test results.

For a more comprehensive and realistic fatigue assessment, this work introduces a modified notch stress approach for assessing the fatigue strength of welded joints, including the effects of real weld geometry and geometric welding imperfections. Although, this approach necessitates further investigations, preliminary results are promising.

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FD25-55

Identification of Plastic Properties in Multi-Material Thin Aluminum Welded Tubes through Experimental Methods, Modeling, and AI

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The growing development of soft mobility, especially electrically power assisted cycles (EPAC), is leading to more complex frame geometry and greater loads. Therefore, the aim of this study, conducted in collaboration with Decathlon, is to enhance the understanding and simulation of the fatigue life of aluminum bike frames. The study specifically focuses on tube welding, a favored crack initiation area. Scientifically, the challenges are centered on the emergence of a property gradient, multi-axial loading, and the thin tubular nature of the concerned areas.

Firstly, to simplify the problem and overcome the difficulties associated to the geometry of bikes frame, micro-tensile tests instrumented by stereoscopic image correlation were carried out on flats shaped specimens to identify the constitutive laws in the different zones of interest close to the welded area.

Secondly, to get closer to the real shape of an aluminum cycle frame, combined tensile and torsion tests on butt-welded tubes were carried out. The instrumentation of these tests is based on stereoscopic image correlation, initially allowing access to in plan and out of plan displacement fields on the surface and subsequently, access to information related to the topology of the weld beads. The study of these kinematic fields has enabled the identification of areas of interest and the recalibration of material properties based on a representative digital model. The test load path was designed to be as representative as possible of the stresses experienced by bike frames during normatives tests.

Regarding the representative numerical model, a tiling of solutions has been proposed to cover a wide range of properties. This database serves to feed an AI model which allows for the interpolation of solutions. Starting from this hypermodel, the data from the stereo correlation are re-injected to identify the real properties. All studies were performed in quasi-static conditions but will be extended to fatigue cases in future actions.

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FD25-69

Ultrasonic fatigue testing of austenitic stainless steels up to a very high number of laod cycles

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Austenitic stainless steels are often used for reactor internals that are subject to mechanical and thermo-mechanical stresses that induce low cycle fatigue (LCF), high cycle fatigue (HCF) and even very high cycle fatigue (VHCF). LCF occurs, for example, in piping materials during heating and cooling cycles in start-up and shutdown operations due thermal stratification. Some nuclear power plant components are additionally subjected to high frequency loading in the HCF/VHCF regime e.g., by thermal striping and flow induced vibrations and their interaction. To investigate the VHCF regime mechanical cyclic loading up to 1010 is required. Therefore, ultrasonic fatigue testing systems (UFTS) with a test frequency of f = 20 kHz are usually used. While LCF and HCF tests are strain or stress controlled, VHCF tests are displacement controlled. Calculation from displacement amplitude to strain/stress amplitude is required. In contrast to high-strength steels and other metallic materials such as aluminium and titanium alloys, displacement-controlled VHCF tests on ASS and UFTS cause serious problems in adjusting the control and test parameters due to the elastic plastic behaviour and, for metastable ASSs, the phase transformation from gamma-austenite into alpha'-martensite. To compare VHCF test results to the ASME standard fatigue curve (total strain amplitude vs. load cycles to failure), a fictitious-elastic and an elastically plastic assessment method was used. The elaborated elastic–plastic assessment method generates good results, while a purely elastic assessment in the VHCF regime, commonly used in literature, leads to significantly nonconservative results. In this work, cyclic loading ap up to the VHCF regime was carried out on AISI 347 and AISI 304L at ambient temperature with load ratio R = -1 using a self-developed UFTS. During fatigue, elastic-plastic deformation occurs in the specimen, which leads to deformation-induced phase transformation and cyclic hardening. The change in the microstructure were investigated in the details using optical and scanning electron microscopy as well as non-destructive magnetic Feritscope measurements.

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High Cycle Fatigue probabilistic modeling of High Pressure Die Casting (HPDC) AlSi9Cu3(Fe)

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High Pressure Die Casting (HPDC), commonly used with aluminum alloys in automotive industry, is a process that produces complex components in a single block, in large quantities and in less time than other casting processes (gravity casting or lost foam casting). However, this process leads to the presence of casting imperfections resulting in poor material health. These include variations in the eutectic phase, intermetallics and the heterogeneous distribution of pores within the parts, which are very often the cause of failure. To ensure structural integrity without the need for additional weight, it is essential to consider the characteristics of defects in the fatigue design of parts.

The aim of our study is to develop a fatigue design approach appropriate to the specific characteristics of HPDC materials and processes. To achieve this objective, a probabilistic Monte-Carlo type approach is developed. The synthetic materials generated are representative in terms of size distribution and spatial distribution of defects.

The approach is applied to cylindrical AlSi9Cu3(Fe) specimens obtained following several manufacturing and post-processing parameters such as two cooling rate and heat treatment (as cast or partial treatment T5). X-ray tomography analyses have shown that the cooling rate is the factor that most influences the heterogeneous characteristics of the defect population in terms of size and spatial position. The internal and surface behavior models developed were applied, depending on the position of the defects. The probabilistic model also considers the competition between internal and surface defects observed with the HPDC process. It has been shown that large defects, generally of the spongy pore network type, are difficult to consider. A gaussian blurring method was used to be representative of the critical defects observed experimentally. The design of the approach enables it to be applied to real components by considering the zones of interest and applying the corresponding size distribution and spatial distribution of defects.

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Modelling of the Test Frequency Discrepancy in USF Testing of Structural Steels

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It is known that the increased testing rate and corresponding reduced test duration inherent in Ultrasonic Fatigue (USF) testing can have a significant influence on the fatigue response of the tested material. Particularly, for Body Centered Cubic (BCC) materials such as ferritic steels, the dislocation glide mechanisms are known to be very sensitive to strain rate, leading to the material appearing to be much stronger when tested at ultrasonic frequencies. This results in the apparent fatigue resistance of structural steels being much higher in USF testing than at conventional frequencies. Until a method can be used to estimate and correct this frequency discrepancy, the resultant USF data for structural steels is of limited practical use.

In this experiment, the fatigue response of several structural steel grades: S355JR, Q355B, S275JR, S275J2, and C45 were evaluated at 20kHz frequency using a Shimadzu USF-2000A machine and at conventional 20-50Hz frequencies using an Instron Electropuls E3000 testing machine. Test parameters such as the specimen geometry and test temperature were kept consistent between the two frequencies to limit the difference in test conditions to just the test frequency. Additionally, high strain rate tensile tests were carried out to evaluate how the materials' strength varies with strain rate.

The frequency sensitivity was evaluated for each of the tested materials based on both the finite life region and the fatigue limit value of the SN curves. Several previously proposed frequency sensitivity models from the literature were evaluated for the tested materials, along with empirical comparisons. The accuracy of these models applied to the tested materials is discussed. Additionally, by comparing the frequency sensitivity results for the tested materials, alongside similar materials in the literature, the influence of the material parameters on the model parameters is investigated.

Finally, the aforementioned models were also adapted and applied as a correction factor to the USF data to attempt to relate the USF response to the conventional frequency fatigue response, with the efficacy of this approach being discussed.

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FD25-122

Fatigue Strength Increase with In-situ Nanolaminate Treatment of Weld Seams in Bridge Construction

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This paper presents a novel technology that reliably contributes to the structural integrity of newly built metal infrastructure. The technology is the nanostructured metallic multilayer (NMM) treatment, which has recently been proven in laboratory testing to increase the fatigue strength of a butt-welded joint (double V-notch) from FAT class 80 to beyond FAT class 190. This paper demonstrates, for the first time, how this novel technology is applied in-situ on a real bridge, provides insights into the processing of the NMM in-situ, discusses the quality of the deposited nanomultilayer, and quantifies the increased fatigue strength and improvement of structural integrity.

Recent research findings demonstrate that the NMM treatment of weld seams considerably enhances the fatigue strength of weld seams and extends the lifespan of the welded joint multiple times.

Within the study described herein, the technology is transitioned into practical application. A deposition apparatus is developed and undergoes initial tests to apply the NMM treatment on welds of a bridge in the port of Hamburg. In a comprehensive study, the ideal configuration of the deposition container, as well as the size and position of electrodes, is determined through numerical simulation of the electroplating process of the nanomultilayer consisting of copper and nickel layers. The numerical simulation allows modeling of the thickness and deposition rate of individual layers.

The deposition apparatus is fabricated by 3D printing plastics. Given the pH level of the electrolyte solution used, it is essential to use an acid-resistant material for printing. The structure has a modular design, allowing the apparatus to adapt to different surface geometries.

In initial experiments, the deposition prototype is tested by applying the metallic nanomultilayer on flat sheets. The deposited multilayers are analyzed using X-ray diffraction (XRD) and electron microscopy, providing insights into the residual stress state and layer structure of the nanolaminate. The findings pave the way for the efficient application of the NMM treatment on fatigue-critical welded joints of the steel infrastructure and potentially ensure readiness and structural integrity of the steel infrastructure.

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FD25-130

Fatigue life assessment of cold-formed ultra-high strength steel sections

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The usage of ultra-high strength steels is ideal for thinner, lighter, and smarter solutions due to enhanced mechanical properties. These designs lead to weight reduction, consequent fuel and energy savings, higher payloads, and material cost savings. Target applications include but are not limited to yellow and green goods, trucks, tippers, cranes, and heavy mechanical equipment, where fatigue performance is critical in design due to cyclic service loads.

Decreasing the thickness of current products for weight reduction results in increased stresses, which make the use of ultra-high strength steels essential. These materials have higher yield and tensile strengths than conventional mild steels and better fatigue resistance. To ensure safety under repeated loading, it must be known that fatigue failure typically originates from stress raisers. These stress raisers can be inherent in the microstructure, due to surface condition, or they result from joining, cutting, and forming procedures.

In this study, we use an in-house fatigue testing setup to consider the complex effect of cold forming in predicting number of cycles of a formed part. Finite-element analysis is used to predict the number of cycles. Utilizing a hybrid approach that combines experimental and numerical outputs, it is possible to define a design space to account the effects of forming parameters such as bending ratio and surface state. The accurate quantification of the effect of cold forming on fatigue life is crucial for the applications with fatigue-critical formed sections and to optimize future designs.

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FD25-136

Effect of prior plastic deformation on the fatigue behavior of a high strength martensitic steel

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Many structural components such as pipings and pressure vessels experience plastic deformation during final cold forming required by joining threaded or welded connections. The effect of prior plastic strain on further resistance to fatigue is scarcely documented in open literature regarding high strength martensitic steels, and controversial effects have been reported.

This work addressed the effect of prior tensile plastic strain on the residual fatigue lifetime and on fatigue crack initiation and propagation mechanisms of a high strength martensitic steel. Polished low cycle fatigue specimens were tested with or without prior tensile deformation up to 4%. Specimens were also cut from an actual component that experienced cold forming up to a few % followed by stress relieving. Manson-Coffin curves were determined for each strain path; damage and fracture mechanisms were investigated using both 2D (scanning electron microscopy) and 3D (X-Ray tomography) techniques. Miniaturized crack propagation specimens were also extracted from the undeformed material and from tensile specimens previously deformed up to 4%, then tested in fatigue.

All stress-strain curves exhibited cyclic softening together with Masing effect; stress amplitudes vs. cycle numbers quickly merged into a single curve until damage development. Prior tensile deformation induced a slight decrease in lifetime, with no change in the Manson-Coffin exponent. The amount of cumulative plastic strain at fracture significantly decreased after prior plastic deformation, whereas the fatigue crack propagation rate increased by about 20%. These phenomena did not depend on the prior deformation conditions.

Several fatigue cracks initiated from persistent slip bands at the side surface of low cycle fatigue specimens. They propagated independently toward the specimen axis, extending up to 25% of the specimen gage radius. Even after deep crack propagation, the specimens failed in a ductile manner by final pulling at temperatures as low as -80°C.

Fatigue striations were detected in fracture surfaces of the crack propagation specimens. Some smooth regions were also detected, also linked to the crystallography of martensite packets but without any sign of cleavage fracture. Under higher stress intensity factors, the density of secondary cracks increased, the fraction of smooth regions decreased and the presence of slip bands in these regions became more visible. Whatever the type of cyclic test, damage and fracture mechanisms did not vary with the application of prior tensile strain. Prior tensile plastic deformation proved an efficient tool to assess the residual fatigue strength of the considered high-strength martensitic steel.

S09
Fatigue of Assemblies

Chairmen:

Hugo Heyraud & Théo Larue

Robin Hauteville & Hugo Heyraud

Isabel Huther & Guillaume Servanton

Yanneck Suchier & Guy Fournel

Isabel Huther & Roderick Jacques

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FD25-3

Automated implementation of structural stress evaluation for weld fatigue assessment in industrial applications

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This paper provides an overview of weld quality inspection for welded structures, focusing on preventing fatigue failures. It highlights the limitations of current quality control systems and discusses international weld quality standards. Additionally, it introduces a new online method for quality assurance, enabling accurate, repeatable evaluation of large quantities of welds. This method integrates digital visual inspection technology, specifically the Winteria system, which captures high-resolution images and uses sophisticated algorithms to detect defects. Winteria's capabilities allow for thorough, consistent weld quality assessments, enhancing process control and robot systems. This advanced system is successfully commercialized and implemented at several manufacturing sites.

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FD25-4

Updated Guidelines on HFMI Treatment for Enhancing Fatigue Strength in Welded Joints: IIW 2nd Edition

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This paper provides an overview of the second edition of the IIW recommendations on High-Frequency Mechanical Impact (HFMI) treatment, a widely recognized technique for enhancing the fatigue strength of welded joints. Based on extensive research and new experimental data, these updated guidelines introduce refined HFMI procedures, comprehensive fatigue assessment methods, and quality control measures. The recommendations are applicable to both new designs and the rehabilitation of existing structures, offering improved fatigue performance for steels with yield strengths ranging from 235 to 1300 MPa and thicknesses between 5 and 50 mm. Key considerations include expanding the recommendations on the effects of variable amplitude loading and the benefits of HFMI for high-strength steels. This version also introduces provisions for treating prefatigued and in-service structures, further extending the applicability of HFMI treatment.

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FD25-13

Life extension using HFMI of notched and prefatigued welded bridge details

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Steel bridges and similar welded structures are highly susceptible to fatigue failure due to repetitive loading and environmental factors. Addressing fatigue in existing structures is critical for extending their service life and reducing the need for costly replacements. This study investigates the use of High-Frequency Mechanical Impact (HFMI) treatment to extend the fatigue life of welded in-plane gusset plates, a detail prone to fatigue and found in many in bridges. Welded joints, susceptible to fatigue failure, were tested under pre-fatigue conditions with existing cracks (0.15 -0.5 mm). The study involved HFMI treatment on notched and pre-fatigued specimens, followed by fatigue testing to evaluate life extension compared to untreated control specimens.

Experimental results showed that HFMI significantly increased fatigue life, with treated specimens exhibiting a life extension towards the life extension of untreated samples. Finite Element Analysis (FEA) was employed to validate strain measurements in conjunction with strain range drop to aid the testing process. The findings demonstrate the effectiveness of HFMI in enhancing the fatigue life of critical welded bridge details and its potential for broader application in bridge maintenance.

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FD25-14

Experimental study on the influence of thinness effect and weld quality of non-load carrying welded joints

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Among several parameters affecting the fatigue life of the welded joints, the size effect and weld quality are the main focus of the current study. Fatigue design technical documents consider the thickness effect by reducing the S-N curve for joints thicker than the reference thickness value. Yet, limited attention has been paid to the thinness effect, where the specimens gain life due to decreasing thickness. Understanding the connection between weld profile geometry and fatigue strength is also imperative for assessing welded joints against repeated loads, as geometrical irregularities lead to local stress raising and decrease fatigue life.

In this study, several fatigue test series were performed on non-load carrying welded joints with 2- and 16-mm thicknesses under uniaxial constant amplitude loading, resulting in S-N curves to analyze the influence of thickness on fatigue strength. For each test specimen, the variation of weld shape along the weld seam is measured using a laser scanning tool. Assessment of fatigue test results and weld profile measured data helps better understand the uncertainty and variation in fatigue life and the relationship between fatigue strength with specimen thickness and the weld quality. The results indicate that there is a beneficial effect from reducing thickness and increased weld quality.

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Stochastic Finite Element Analysis for Fatigue Life Assessment of Welded Assemblies

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Ageing of hydraulic structures such as, pumped-storage power plants, rotating machinery (turbines, rotors, etc.), and locks...etc, compels managers to choose among several scenarios: extending the service life, performing repairs, reinforcing, or even complete replacement. Such structures, that naturally experience variable (cyclic) loading over time due to their operation, are generally assemblies of plates and beams, which present stress concentration zones, particularly around weld seams. The risks of crack initiation and propagation due to fatigue are often located near these areas.

Fatigue behaviour is an inherently random phenomenon, characterised by various uncertainties related to loading conditions, mechanical properties, material characteristics, manufacturing quality, geometry, and other variables.

Initially, international design codes and standards are irrelevant, focusing on lifespan estimation during the initial design phase, making them inapplicable to scenarios requiring an extension of the operational life. Despite the existing research and studies concerning estimating the fatigue life, the stress–life relation, the probabilistic fatigue curves (P–S–N) of mechanically welded metallic structures (Mikulski and Lassen, 2022; Rocher et al., 2020; Schubnell et al., 2024), and fatigue assessment using stochastic finite element (SFE) models (Larsen et al., 2021; Singh et al., 2020). Only a few studies have addressed the fatigue assessment of lock gates, using SFE models, e.g. (Estes et al., 2004; Ramancha et al., 2022).

In light of these considerations, this paper proposes a probabilistic fatigue approach, based on fracture mechanics analysis and combined with SFE modelling at the scale of structural-steel welded assemblies. A comparison of different international design codes and standards (EC3: EN 1993-1-9, 2005; BS 7608, 2014) will reveal scientific challenges, potential gaps, and discrepancies that might influence fatigue life assessment, providing a broader perspective to gauge the proposed approach's potential in enriching fatigue calculations.

This work emphases local stochastic characterisation of fatigue crack propagation in welded assemblies. Influencing factors are modelled as random variables, allowing uncertainties to propagate throughout the FE mechanical model. The post-processing of the generated meta-model, based on an implicit analytical function derived from the Paris law, allows conducting a probabilistic assessment of the remaining useful life (RUL). The resulting cumulative distribution function providing the probability of failure for a given failure criterion, serves as an alert tool for maintenance and risk management, helping operators in planning inspections and interventions to ensure the long-term security and reliability of ageing structures.

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Prediction of fatigue life for butt-welded joints using multi-fidelity surrogate modelling

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Welding has been considered as one of the most efficient and reliable joining technologies in fabricating metallic components. However, imperfections and/or defects in the welded components are inevitable during and after the welding process which have significant effect on weld quality as well as integrity of the finished products. For this reason, the standards for weld quality assessments are issued by various regulatory bodies in which the limits for occurrence or dimensions of imperfections are described. However, in some studies, welded joints in low quality category are found to have higher fatigue strength than those with high weld quality specification. These studies reveal the need to consider the fatigue strength in relation with the standards of imperfections while specifying the quality of a welded component. Fatigue strength assessments are often performed using experimental approach which requires extensive man-hours and cost. On the other hand, numerical methods are also widely used to determine the fatigue life of welded components. However, parameter uncertainties can lead to inaccurate results and considering weld defects takes considerable computational hours.

In this regard, multi-fidelity surrogate models are considered as one of the promising approaches for fatigue strength predictions. They are developed and trained using the data constructed from high-fidelity models which are calibrated using experiments, and low fidelity ones which are simplified versions of high-fidelity models. In this study, a multi-fidelity surrogate model which can predict the fatigue life in relation to the weld quality was developed for butt-welded joints containing imperfections. Different from other machine learning models and conventional assessments, the proposed model can provide fatigue strength predictions while keeping the balance between accuracy and computational efficiency by taking advantage of high- and low-fidelity models. The methodology and procedures in developing surrogate model as well as the predictions and findings given by the model are discussed. Furthermore, extending the geometry of the welded joints and types of imperfections will make this surrogate model versatile and robust for practical applications.

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Introducing Superelements for Weld Fatigue Analysis

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Weld cracks play a significant role to fatigue failure, making the accurate modeling of both spot welds and seam welds crucial for structural durability. In the automotive industry, various methods, such as nominal stress or force-based approaches, have been employed for weld fatigue analysis. Nevertheless, incorporating local stress directly yields more precise results. However, this method is based on very fine meshes for the detailed examination of local notch stress, which leads to substantial computational demands.

To address this challenge, the superelement approach is introduced. This method involves generating the superelement welds, positioning them within the full assembly, recovering stress components of the notch and calculating fatigue life. For seam welds, accurate placement along the weld line is particularly challenging. A constant radius of the weld describes the notch geometry and von-Mises stress is used as the fatigue criterion.

This work involves the analysis of component with welds, providing a thorough description of the entire process and the challenges faced. Comparisons between the superelement welds and those with detailed geometry are also presented to evaluate the method and highlight its advantages.

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HFMI-treated welded structures: fatigue strength assessment based on the Peak Stress Method

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High-frequency-mechanical-impact (HFMI) is a post-weld treatment for improving the fatigue strength of welded structures, by introducing compressive residual stresses, localized strain hardening and enlarged weld toe radii. The Peak Stress Method (PSM) has been recently extended to the fatigue strength assessment of HFMI treated steel joints, by means of a dedicated analysis procedure and new fatigue design curves, calibrated on experimental data generated from HFMI treated joints tested under uniaxial loading with nominal load ratios R = -1, 0.1 and 0.5. The results were taken from the literature and relevant to structural steels having yield stress in the range $355 \le \sigma y < 750$ MPa. In the present work the applicability of the PSM to analyse HFMI treated welded joints has been extended by calibrating new PSM-based fatigue design curves on experimental results taken from the literature and generated by adopting nominal load ratios in the range $0.1 < R < 0.5$. Moreover, experimental data generated from joints made of structural steels having yield stress $\sigma y < 355$ MPa or $\sigma y > 750$ MPa have been analysed for the full range of the nominal load ratio R to calibrate proper PSM-based fatigue design curves.

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Optimizing Welded Structures: A Study on the Integration of Recent Technological Development

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This paper investigates the transformative effects of integrating advanced technologies related to design, calculation, and production processes of welded structures within the construction machinery industry. In an environment where demands for product development speed, lean production, and sustainability are increasing, traditional methods for design and manufacturing have proven to be inadequate. The «Welded Structures 4 Tomorrow» (W4T) initiative responds to these challenges by incorporating cutting-edge technologies, particularly in fatigue analysis, to enhance efficiency, product performance, and environmental impact.

A key focus of the W4T program is a new innovative fatigue analysis method that reduces the conservatism inherent in traditional approaches. This method concentrates on crack-driving stresses and the direction of crack propagation, allowing for a more precise evaluation of structural integrity. By targeting material usage more accurately, the approach optimizes the weight and strength of welded structures, facilitating design and manufacturing adjustments that enhance both performance and efficiency.

These innovations extend beyond analysis to improve manufacturing processes. With a better understanding of where stresses occur and how cracks propagate, production can be streamlined to reduce welding volume and post-weld treatments, thereby lowering CO_2 emissions and conserving resources. Additionally, efforts to accelerate CAD modeling for stress analysis allow for faster design iterations, reducing dependency on specialized skills and supporting quicker decision-making during both conceptual and detailed design phases.

The integration of 3D laser cutting for weld preparation and robotized TIG dressing for post-weld treatment complements the enhanced fatigue analysis method, ensuring manufacturing processes align seamlessly with optimized designs. Furthermore, the use of digital twins enables a more accurate understanding of machine usage and load data, reducing conservatism and improving fatigue life predictions.

By combining these technological advancements with optimized manufacturing workflows, the W4T program significantly improves design, analysis and production efficiency. The result is lighter, more cost-effective welded structures that meet rigorous performance and sustainability goals. This paper demonstrates how innovative fatigue analysis and manufacturing techniques can drive significant advancements in product quality while ensuring competitiveness in a rapidly evolving market.

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Fatigue strength verification of bearing type joints with mechanical fasteners – A comparison of Eurocode 3 and effective notch stress concept

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The fatigue strength verification is a key factor in the design of cyclical loaded steel and lightweight steel structures. In particular, mechanical fastened joints represent hotspots in the structure that require special attention. The fatigue strength assessment acc. to the Eurocode 3 Part 1-9 based on the nominal stress concept with defined detail categories for different structural details. This method is still the preferred verification procedure in many technical areas. Most of the influencing variables on fatigue resistance as mean stress level, residual stresses, material strength, notch effects etc. are already covered by the corresponding detail category of a structural detail. This allows verification to be carried out without the need for precise knowledge of these influencing variables in the verification. Associated with this is also a conservatism in the design of some of the structural details from the Eurocode 3 Part 1-9, which is demonstrated by new studies on the fatigue resistance of bearing type connections with mechanical fasteners. In these studies, the material strength and the joint configuration (single or double lap joints, variation of hole and edge distances, number of fasteners) were systematically changed to determine their effects on fatigue resistance.

A promising alternative is the verification according to the effective notch stress concept for non-welded structural details. This concept makes it possible to consider two main effects for bearing type connections in the design, particularly the material strength of the components and the notch effect. Cause of the missing preload in bearing type joints they transmit the external actions by bearing contact. The bearing contact results in a combination of different stress increasing effect in the components, which requires a more detailed description by numerical studies for verification. By comparing the fatigue strength from test-assisted S-N- curves (nominal stresses) with synthetic S-N curves (effective notch stress concept) the deficits of the existing design rules are highlighted. In addition, a new design proposal for the bearing type joints with mechanical fasteners based on the notch stress concept is proposed.

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The Peak Stress Method combined with shell finite element models for the fatigue design of complex welded structures

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The Peak Stress Method (PSM) is a rapid FE-oriented local approach to evaluate the Notch Stress Intensity Factors (NSIFs) as a function of the singular linear-elastic local peak stresses calculated at the weld toe and at the weld root by exploiting relatively coarse free meshes of 2D four-node plane and 3D eight-node brick as well as four-node and ten-node tetrahedral solid finite elements. The PSM can be combined with the averaged Strain Energy Density (SED) fatigue criterion to define a design stress, the so-called equivalent peak stress. In turn, the equivalent peak stress enables to estimate the fatigue lifetime of steel welded joints under both constant amplitude (CA) and variable amplitude (VA) uniaxial and multiaxial loadings, in compliance with PSM-based fatigue design scatter bands previously validated against approximately 2000 experimental data relevant to weld toe and weld roots failures in steel welded joints. Moreover, a dedicated fatigue analysis tool, the so-called "PSM App", has been recently developed in Ansys® Mechanical to implement the analysis workflow of the PSM and provide support to the FE analyst in the fatigue design of complex welded structures.

The adoption of shell finite elements provides the opportunity to (i) furtherly reduce the size of FE models if compared to solid finite elements and (ii) rapidly analyze large-scale structures. Accordingly, the applicability of the PSM combined with shell finite element models has been investigated. In this work, the PSM has been calibrated by considering both four-node linear and eight-node quadratic shell elements available in the Ansys® element library. In addition, a dedicated procedure is presented, which enables the FE analyst to apply the PSM by adopting shell FE model. Eventually, an industrial case study is presented, which deals with the fatigue durability of a large-scale complex steel welded amusement park structure subjected to multiaxial loadings. The mesh density and solution time required to apply the PSM to the structure under exam by adopting four-node or eight-node shell elements have been compared with those required by a 3D 10-node tetrahedral FE model of the structure. The "PSM App" has been employed to assess the fatigue strength of the structure under exam by implementing the newly developed analysis procedure.

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Evaluating the fatigue strength of aluminium fillet-welded joints under multiaxial variable amplitude loading using the Peak Stress Method

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Aluminium alloy welded structures are widely used in lightweight engineering applications due to their high strength-to-weight ratio. Unfortunately, their susceptibility to fatigue failure poses significant challenges for engineers, since traditional fatigue life prediction methods struggle to accurately account for the complexities introduced by in-service loads, which are typically multiaxial and Variable Amplitude (VA). This study addresses this challenge by employing the Peak Stress Method (PSM), an engineering technique designed to exploit the Strain Energy Density criterion to efficiently estimate the fatigue strength of welded joints. Specifically, the PSM is a finite element (FE)-based method that rapidly evaluates the Notch Stress Intensity Factors (NSIFs) at critical locations, such as the weld toe and root, modelled as sharp V-notches with null tip radius. The PSM has previously demonstrated strong capabilities in assessing fatigue strength under Constant Amplitude (CA) loading and, in recent developments, the PSM formulation has been adapted for VA loading by integrating a cumulative damage rule. This research further extends the application of the PSM to multiaxial variable amplitude loading conditions for welded joints in aluminium alloys. The proposed approach is validated against experimental data on non-load carrying (nlc) fillet-welded double transverse or inclined attachments made of 6082-T6 aluminium alloy subjected to variable amplitude in-phase multiaxial local stresses. The results highlighted some apparent discrepancies between the theoretical estimations of the PSM and the experimental fatigue lives of joints with inclined attachments, which must be attributed to an extended crack propagation phase. Accordingly, the present work investigates the extent of the fatigue crack propagation phase under both uniaxial and multiaxial as well as CA and VA loading. More in detail, it incorporates experimental measurements made by using the Direct Current Potential Drop (DCPD) method and numerical simulations of the propagating fatigue cracks. The results provide insight into improving the accuracy of fatigue life predictions, proving the PSM to be a reliable tool for the design of aluminium welded structures subject to in-service loads.

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Fatigue Tests on Butt-Welded Connections With Imperfections

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The design resistance in prEN 1993-1-9 for welded connections subject to fatigue loading refers to ISO 5817 quality level B. However, the background document does not explicitly support the link between weld quality level and fatigue resistance. To address this gap, an analysis was conducted on the experimental database used for prEN 1993-1-9, in conjunction with published results from literature encompassing over 1000 experimental fatigue tests. In addition, experimental tests were conducted on butt weld connections welded from one side to evaluate the impact of undercut on fatigue strength. Non-destructive testing methods, including 3D scanning, and radiographic testing were employed to characterize weld imperfections. Fatigue strength was evaluated in accordance with prEN 1990 requirements. The findings revealed that mean undercuts height between 0.54 mm and 1.48 mm in a 15 mm plate thickness have decreased the fatigue strength to 62 MPa (13% reduction). Moreover, the analysis revealed that some experimental tests used in the background document did not conform to quality level B tolerance. Finally, the use of 3D scanning provided detailed measurements of geometric imperfections that cannot be captured by visual inspection, which may downgrade the quality levels to D or below. This highlights the need to align weld quality classifications with the non-destructive test method employed.

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Advanced Machine Learning-Based Durability Assessment of Spot Welds Addressing Mode II and III Loading

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Spot welds play an important role in automotive structures and therefore these joints need to exhibit good reliability under durability loading over the lifetime of the vehicle. For many years, numerical methods for estimating their durability performance exist. They can be subdivided in structural and notch stress approaches as well as approaches that use fracture mechanics. However, the common approaches are developed to reliably predict crack initiation under Mode I loading conditions. This can lead to a non-conservative dimensioning und subsequently to failure in service in cases where in-plane or out-of-plane shear dominates.

This paper proposes a multi-scale approach to account for additional Mode II / III loading using stress intensity factors. Two parametric model are used to set up a limited number of macro- and meso-scale models from which the correlation between forces and moments and local SIF at spot weld is evaluated. To reduce the computational effort in practical application, a machine learning model is trained that estimates SIFs. This model can be used to reliably assess spot weld fatigue performance in full body analyses. The model is validated based on selected fatigue test data.

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Experimental and numerical study on the effect of interference on shrink-fitted assemblies under fretting-fatigue solicitations

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Shrink-fitting is a commonly used process to tightfit mating components such as axles and wheels or sleeves. An important range of applications exists in the railway and maritime industries. Such assemblies are submitted to complex multiaxial fatigue loadings including rotatory bending, compression and torsion. Moreover, differential deformations between the two parts can induce local fretting damages, leading to wear or crack nucleation.

The aim of this study is to describe the impact of interference value on fretting-fatigue behavior and thus on lifetime. No consensus exists in scientific literature concerning this problem. The modification of interference value has a direct impact on contact pressure, and therefore also on local stresses and on sliding amplitude, which are driving factors of fretting solicitations. Impact on the lifetime seems however to be heavily dependent on the range of induced contact pressure, which is in the studied application very low given the large size of the contact. Coupled experimental and numerical studies will be carried out.

Experimental studies will focus on a simplified loading case, i.e. rotary bending, using two specifically designed test benches. The test specimen is a steel shaft with shrink fitted bronze sleeve, which is a scale representation of a maritime drive shaft. Tests will be carried out on an extended range of interference values to obtain fretting-fatigue S-N curves. Damage characterization will focus on fretting wear debris and cracks. The third body layer, which is thought to control crack nucleation, will be precisely quantified using a new disassembly-free measurement protocol.

FEA modeling will be carried out in parallel, with the aim of improving our understanding of the phenomenon and developing a life prediction model. Interference fitting and bending will be considered, as well as friction at the interface, to obtain local contact data such as slip and surface shear. Wear will also be considered to ensure correct modelling of the phenomenon. Multiples tribological and multiaxial fatigue criteria will be implemented as post-treatment to quantify fretting-fatigue damage.

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FD25-118

Results of the Jaco project: Effect of in-plane and out-of-plane loading on the cracking behaviour of tubular joints during large-scale tests

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Tubular joints are common in offshore structures, among others for foundations for wind energy convertors. In the JaCo project, large-scale fatigue tests were performed in-plane and out-of-plane on 45° joints. A consistent different cracking behaviour was observed between joints loaded in-plane compared to joints loaded out-of-plane. The in-plane loaded joints fail by cracking through the brace, after crack initiation at the crown heel and a limited crack growth in the width. The stiffness of the joint is also almost constant until failure. Cracks initiate at the saddle points in out-of-plane loaded joints and propagate along the weld toes, reaching a very large width. A significant decrease of the joint stiffness is observed at failure, allowing for a redistribution of the load during the test. Consequently, the cracking in out-of-plane is much more progressive than in-plane. Although the fatigue life in design rules is described by the same S-N curve for the heel and the saddle points, it was found that the fatigue life for in-plane loading is shorter than for out-of-plane loading, highlighting a limitation of the current hot spot method.

S10

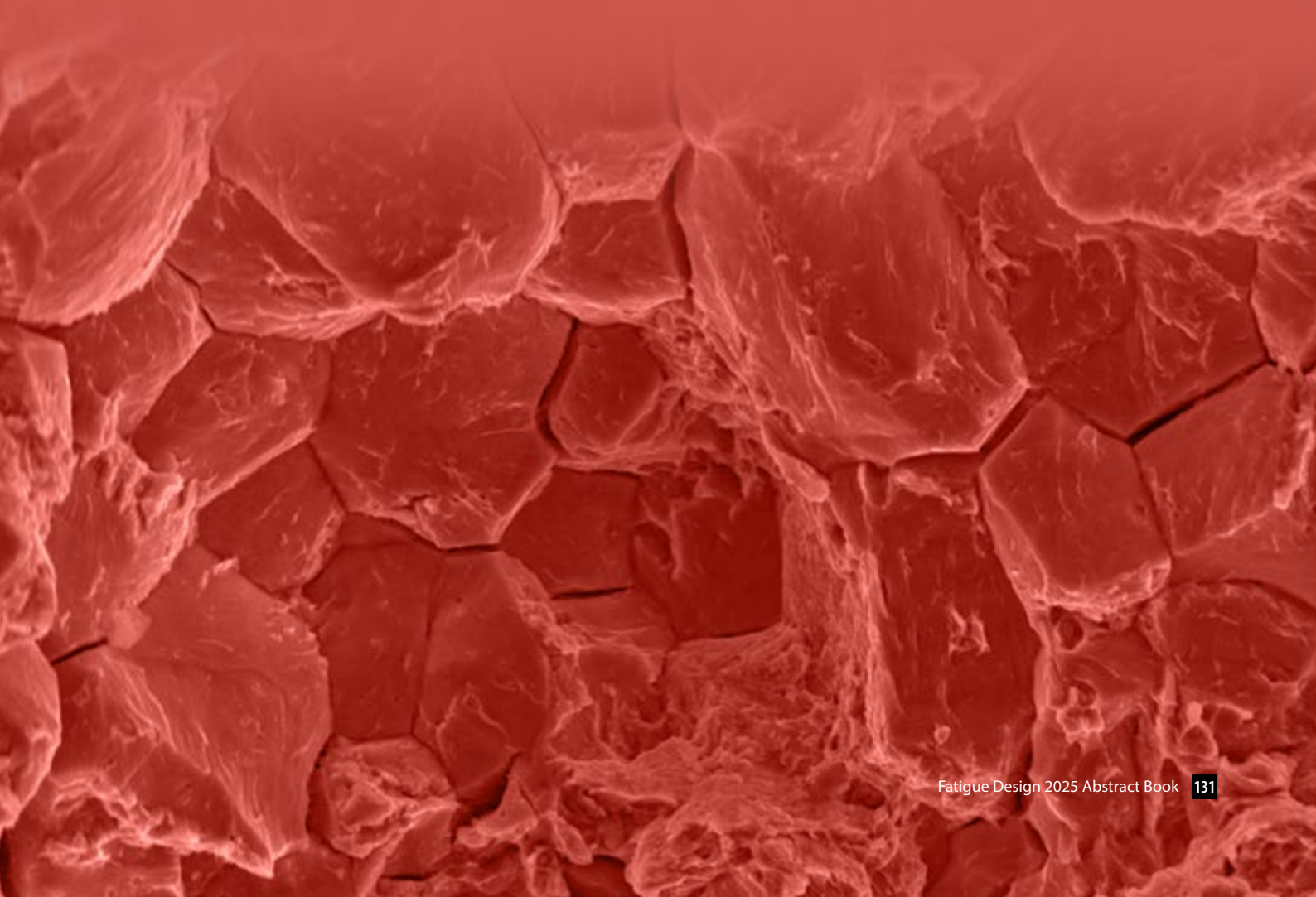
Fatigue under Severe Environmental Conditions

Chairmen:

Gouenou Girardin & Pierre Osmond

Gouenou Girardin & Marie Lemaitre

Gouenou Girardin & Thomas Landron



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FD25-6

Component Dimensioning in Hydrogen Environment

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For the ongoing energy transition, high pressure hydrogen is a highly relevant energy carrier. In order to provide a practical and robust hydrogen infrastructure, a vast variety of components needs to be developed to ensure a save hydrogen storage and transport. Dimensioning of these parts with respect to their structural durability requires new dimensioning schemes and guidelines to be developed which account for material specific damage mechanisms under hydrogen environment. An ideal basis represents the well-established FKM guideline issued by the German Research Association Mechanical Engineering (FKM). The guideline is applicable for a wide range of mechanical engineering components and is particularly popular for small and medium enterprises (SME). Within our research project, the dimensioning scheme based on the FKM guideline is applied for exemplary structural parts in hydrogen environment. Based on literature data and experiments conducted within the project, a dimensioning scheme is developed specifically for a sample component. In our presentation, we analyze existing dimensioning codes and material data under hydrogen environment and discuss how the FKM approach needs to be adapted to consider the hydrogen effects on material and component strength.

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Experimental investigation of the environmentally assisted fatigue crack initiation mechanisms in austenitic stainless steel 304L

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Austenitic stainless steels, mainly grades 316L and 304L, are used to manufacture primary piping components in Pressurized Water Reactor (PWR) nuclear power plants. The thermal fluctuations and expansions to which these components may be subjected during operation induce loading comparable to low-cycle fatigue (LCF) under strain control. These steels are also exposed to a potentially corrosive environment, the primary PWR environment (light water at 325°C and 150 bar). Environmentally-assisted fatigue can lead to a reduction in the fatigue life of these materials. While the impact of the environment on fatigue life is well documented, the role of the environment on the mechanisms of crack initiation and propagation is much less understood.

Several studies have shown that transgranular cracks initiation mode is predominant under LFC conditions. Micro-cracks formation occurs at the surface in 3D dislocations structures, known as Persistent Slip Bands (PSBs). These structures are the result of the deformation localization in the grains during cyclic loading. The irreversibility of dislocations movements leads to the formation of a surface relief composed of extrusions and intrusions. Previous work has also identified a critical extrusion height of about 250 nm above which a crack can be observed in air at 20 °C.

The studies also showed that the environment has an impact on the initiation kinetics, which explains the fatigue life reduction in the primary PWR environment compared with the fatigue life in vacuum and air. The greater reduction in the primary PWR environment is explained by chemical interactions between the environment and the metal in zones with increased plastic activity, the PSBs.

The aim of the present study is to understand the effect of the environment (vacuum, air, light water) on fatigue crack initiation mechanisms. Local and multimodal characterizations will therefore be carried out at initiation sites from the PSBs formation to the micropropagation in the three environments.

To this end, interrupted or multi-interrupted LCF tests will be carried out in vacuum, air and primary PWR environment. Test conditions, especially the prescribed strain amplitude and strain rate, are set to observe a significant effect on fatigue life in the presence of the primary PWR environment. Following these tests, several observations will be made at the scale of one or more grains (SEM, EBSD), then at the scale of PSBs and associated dislocations structures (FIB-cut, TEM). The observations made will also enable analysis of variations in local chemical composition (EDX, EFTEM, EELS).

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Effect of loading waveforms on fatigue crack growth in pipeline steel in high pressure hydrogen gas

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In recent years, hydrogen energy has gained attention as a solution to the increasingly severe issue of global warming, with underway plans to develop hydrogen infrastructure using pipelines for transport. Pipelines are subjected to cyclic stress due to gradual fluctuations in the internal hydrogen gas pressure during operation. In pressurized hydrogen gas environment, the strength of materials decreases compared to that in air—a phenomenon known as hydrogen embrittlement—which can cause crack propagation even under small stresses. Therefore, it is essential to understand the effects of hydrogen embrittlement caused by high-pressure hydrogen gas in pipelines and incorporate this knowledge into strength design to ensure safety and potentially reduce costs.

However, loading patterns used in previous studies have been biased, either by continuously loading specimens until fracture, as in tensile and fracture toughness tests, or by repeatedly applying very small sinusoidal stresses compared to the yield stress, as in fatigue crack growth tests. This study conducted cyclic loading and constant load-holding tests using triangular and trapezoidal waveforms with high loads and low frequencies under a high-pressure hydrogen gas, with the goal of simulating hydrogen pipeline operation in a more realistic way. The test results showed that crack growth was greater in tests using triangular waveforms than in those using trapezoidal waveforms, which included a load-holding phase.

Further post-mortem analysis included fracture surface observation, three-dimensional measurement of the fracture surface, and FEM analysis to investigate the effects of cyclic loading and load-holding on crack propagation from a practical perspective. Additionally, the Crack Mouth Opening Displacement (CMOD) value, measured with a clip-on gauge, gradually increased during load-holding in high-pressure hydrogen gas. To verify the accuracy of the measurements, the drift of the clip-on gauge was checked by leaving the specimen unloaded in high-pressure hydrogen gas for an extended period. The series of experiments suggested the possibility of hydrogen-enhanced crack blunting ahead of the crack tip though further examination is necessary to confirm its validity.

Moreover, deformed microstructures in the vicinity of the crack tip has been investigated in more details using Electron Channeling Contrast Imaging (ECCI) on specimens subjected to constant load-holding tests in both air and hydrogen gas. Based on these tests and observations, the potential of creep induced crack evolution in materials under high-pressure hydrogen gas was also examined.

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FATIGUE DESIGN 2025

FD25-97

Hydrogen-affected fatigue crack growth of Nickel alloy 625: effect of pressure

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Nickel alloys are widely used in various applications that require high pressure and temperature resistance. With the increased use of hydrogen, several nickel-based components may be exposed to hydrogen gas. These applications include the nuclear industry, compressor components, aeronautical piping, and gas storage tanks. Inconel 718, known for its excellent mechanical properties at high temperature, has been extensively studied under hydrogen exposure, both in solution and under gas pressure. Despite its outstanding performance, this alloy is not commonly used in industrial applications due to its high cost, which makes it less suitable for industrial piping systems.

Given these considerations, nickel alloy 625 presents itself as a promising alternative to Inconel 718 for such applications. Alloy 625 offers a more cost-effective solution while still providing good mechanical properties. However, unlike Inconel 718, only few studies has been published on the effect of H2 on fatigue performances. This lack of research is significant.

The aim of this study is to investigate the performance of nickel alloy 625 when exposed to hydrogen gas under various fatigue crack growth conditions. The Hydrogen-Affected Fatigue Crack Growth is characterized by both the hydrogen gas pressure and the stress intensity factor range, . Specifically, the study focuses on the alloy's sensitivity to hydrogen pressure, with fatigue crack propagation experiments conducted at pressures ranging from 0.3 to 30 MPa. A detailed analysis of fracture surfaces is provided to clarify the fracture modes and understand the mechanisms of hydrogen's effect on fatigue crack growth. Furthermore, hydrogen susceptibility is discussed by comparing the hydrogen-affected fatigue crack growth rates observed in nickel alloy 625 to the typical response of Inconel 718 and austenitic steels as reported in the literature

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FD25-102

Hydrogen effect on the self-heating response under cyclic loading of R5 and R6 HSS used for offshore mooring chains

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The upscaling of Wind Turbines puts tough materials challenges to ensure structures integrity and reduce the CAPEX and OPEX of offshore industry. For structural optimized design, a particular attention must be paid for dimensioning mooring chains and select the appropriate High Strength Steel (HSS). One of the main issues remains the assessment of fatigue and fatigue-corrosion properties of the selected materials in such environment. To prevent corrosion, new coatings are being developed to meet current standards. However, the coating process induces hydrogen introduction in the material which could modify its fatigue properties and presents a risk of hydrogen embrittlement given the sensitivity of these materials to this phenomenon.

A number of research has been interested in characterizing fatigue properties from self-heating tests under cyclic loadings. This method is commonly used to study the fatigue of a wide range of several materials. However, the effect of hydrogen on fatigue in the HCF domain has not yet been addressed. This study aims to assess this effect using self-heating method which deals with the temperature monitoring during cyclic loading. A special attention has been given to highlight the role of initial hydrogen content on the self-heating behavior of R5 and R6 HSS steels by setting up and experimental protocol to enable ex situ hydrogen charging and hydrogen content control and then perform self-heating tests on hydrogen charged specimens. Regarding the results obtained in different studies, the influence of hydrogen content on the self-heating curve could indicate that the fatigue properties of these materials are affected.

This study has enabled to contribute towards the prediction of fatigue properties from self-heating results. Classical fatigue tests have been performed to confirm the conclusions made from self-heating results.

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FATIGUE DESIGN 2025

FD25-107

Effect of temperature and hydrogen on fatigue properties of austenitic stainless steel

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The design of liquid hydrogen tanks requires a thorough assesment of the factors influencing fatigue resistance at cryogenic temperatures of austenitic stainless steel alloys in hydrogen environments.

In these materials, Hydrogen Embrittlement (HE) is commonly associated with a reduction in tensile ductility, with a peak embrittlement occurring around -80°C and diminishing at very low temperatures. This study aims to evaluate the high-cycle fatigue resistance of two austenitic stainless steel grades, namelty 304L and 316L, in a hydrogen environment over a temperature range of -120°C to 100°C with a stress ratio R=0.1. A special focus is placed on the individual effects of hydrogen diffusion, as well as strain-induced phase transformations, especially at low temperature. The role of internal hydrogen is also considered; for this purpose, samples were pre-charged with hydrogen gas at 350°C for 96 hours under a pressure of 15 bar, and then tested in fatigue in air and in hydrogen gas. The quantity of hydrogen retained in the materials is evaluated through the use of thermal desorption spectroscopy (TDS).

The results on the coupled influence of temperature and hydrogen on fatigue strength are presented in two parts. The results indicate that the fatigue life is longer when the temperature is lower, given the same stress amplitude. It comes out that the exposure to hydrogen gas has no significant effect on the ratcheting deformation observed under a stress ratio of 0.1, but it does affect fatigue life at higher stress levels when exposed to a hydrogen pressure of 1.5 MPa. The influence of external hydrogen appears to be more pronounced than that of internal hydrogen.

The impact of martensitic transformation at low temperatures on fatigue strength in the presence of hydrogen is also examined. Finally a correlation between crack initiation and ratcheting behavior is proposed.

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FATIGUE DESIGN 2025

FD25-119

On the Use of Hollow Specimen to Characterize the Fatigue Crack Growth in High Pressure Hydrogen Gas

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The use of hollow specimens for the mechanical testing of metals in gaseous hydrogen environments has gained significant attention over the past five years. Numerous laboratories are investigating this test rig, which offers several advantages, including low implementation and operational costs, as well as safety reduced constraints. However, this test remains limited to unnotched geometrical configurations, thus excluding its use for fracture mechanics tests, especially for the characterization of toughness and crack propagation in hydrogen environment.

The objective of this paper is to explore the possibility of modifying the existing hollow specimen test design for the characterization of fatigue crack propagation in gaseous hydrogen environments. To achieve this, the modification of the specimen geometry is studied by finite element analysis using the Zset software suite and the Zcrack module, which allows the explicit simulation of fatigue crack propagation REF. A new geometry is proposed that incorporates a notch on the inner surface of the specimen. Crack propagation modeling is used to qualify the crack propagation from this notch for different crack shape assumptions, all of which converge to a homogeneous case which is favorable for fatigue crack propagation kinetic analysis. In addition, these propagation simulations are used to test the capability of conventional crack size measurement techniques: the compliance method and the direct current potential drop (DCPD) technique. The analysis demonstrates the clear superiority of the DCPD technique, which offers good sensitivity to crack growth, providing sufficient conditions for precise tracking of crack propagation

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FD25-126

Effect of hydrogen gas precharging on the mechanical properties and Fatigue life of Inconel 718 obtained by L-PBF homogenised and aged: From room to intermediate temperature

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The use of Hydrogen combustion as energy source for aerospace applications would result in the exposition of critical parts, such as turbojet injectors, to complex thermomechanical loading in the presence of high-pressure hydrogen gas. However, it's well known that, a long-term exposure to hydrogen can lead to a deterioration in the mechanical properties of metals and a premature failure known as hydrogen embrittlement.

Hydrogen embrittlement (HE) is strongly material and loading dependent, and can operate through several mechanisms. These mechanisms include Hydrogen Enhanced Localized Plasticity (HELP), Hydrogen Enhanced Decohesion (HEDE), Adsorption-Induced Dislocation-Emission (AIDE), Hydrogen Enhanced Strain-Induced Vacancy (HESIV) and their synergistic effects.

The goal of this study is to characterize how HE will affect additively manufactured Inconel 718, a key alloy for designing complex turbojets parts. Specifically, the study focuses on the characterization of fatigue life reduction induced by H intake, and the underlying mechanisms.

The Inconel 718 used in this study is obtained by Laser Powder Bed Fusion, L-PBF, followed by homogenization and aging to annihilate the columnar grain structure and the anisotropic microstructure characteristic of L-PBF and to precipitate the second-phase particles of the material.

Mechanical tests are carried out on the specimens precharged with hydrogen gas in a furnace operating at 400bar and a temperature of 200°C, to study the effect of hydrogen concentration on the alloy's cyclic viscoplastic behaviour. Hydrogen thermal desorption mass spectroscopy are carried out to measure the quantity (concentration) of hydrogen in the material and to identify the quantity of H trapped and in solution.

After the specimens precharging with hydrogen gas, monotonic loading and Oligo-cyclic fatigue tests under isothermal conditions are carried out for a specified temperature range from ambient to intermediate temperature, in order to assess the impact of Hydrogen pre-charging on the fatigue life and mechanical properties of the material in this temperature range. The cyclic loading carried out help to identify the material's cyclic viscoplastic behaviour.

To better understand the role of microstructure on the deformation mechanisms associated with the presence of hydrogen, micromechanical tensile tests under SEM are also carried. Nano-indentation and electron microscopy characterizations (TEM, SEM) are also envisaged, which will be correlated with thermal desorption spectrometry (TDS) analyses of hydrogen concentration and states (trapping detrapping, interstitial diffusion) to study hydrogen segregation in the specimens tested, as well as its effect on the microscopic plasticity of the material.

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FATIGUE DESIGN 2025

FD25-159

Effect of seawater on the fretting fatigue endurance of crossed steel wires: application to floating offshore wind turbines mooring line

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The mooring of floating wind turbines is an important challenge for the offshore industry. It is an important part of the design engineering and, often, a critical point for the fatigue life assessment. A solution that could improve the fatigue life is to directly connect the mooring rope to the floating platform, without an intermediate chain. However this solution can generate fretting fatigue near the connexion, because of the local combined loading: tension and bending. This study investigates the fretting fatigue endurance of crossed steel wire contacts (σY = 1800 MPa et σU = 2085 MPa), representative of steel wire ropes used as mooring ropes. The experimental campaign focuses on the influence of contact displacement amplitude under constant fatigue stresses and normal load. A characteristic "U"-shaped fatigue life curve is observed under dry air condition, with a minimum at the transition between partial and gross slip regimes. This usual behavior can be explained by the fact that, under partial slip conditions, increasing the displacement amplitude increases the tangential loading and therefore reduces the fatigue life. However, once the gross slip transition is overpassed, wear becomes the dominant mechanism (while the tangential load remains constant). This wear simultaneously leads to an expansion of the contact area, which reduces the fretting loads (cyclic shear), and to the removal of microcracks initiated at the surface. These two combined effects result in a rapid increase in fatigue life.

To account for the effect of seawater associated with this offshore application, the same experimental study was carried out in a seawater-immersed environment. Unlike contact in dry air, the evolution of endurance now exhibits a "U–L shape." In this case, the presence of seawater significantly complicates the contact response due to two competing effects: on one hand, a positive lubricating effect of the seawater, and on the other hand, the detrimental influence of corrosion phenomena.

For partial slip conditions and the beginning of the gross slip domain up to a displacement amplitude of ±150 µm (the "U" part of the endurance curve), the positive lubricating effect of seawater dominates, resulting in a decrease in the partial slip/full slip transition and, more importantly, in longer lifetimes under seawater conditions compared to dry contacts. Conversely, for larger sliding amplitudes (> ±150 µm), the relative displacements favors the circulation of the corrosive medium within the interface, which enhances corrosion processes and ultimately reduces the fatigue life. A further drop in endurance is then observed (the "L" part of the endurance curve), with lifetimes significantly lower than those obtained in dry air.

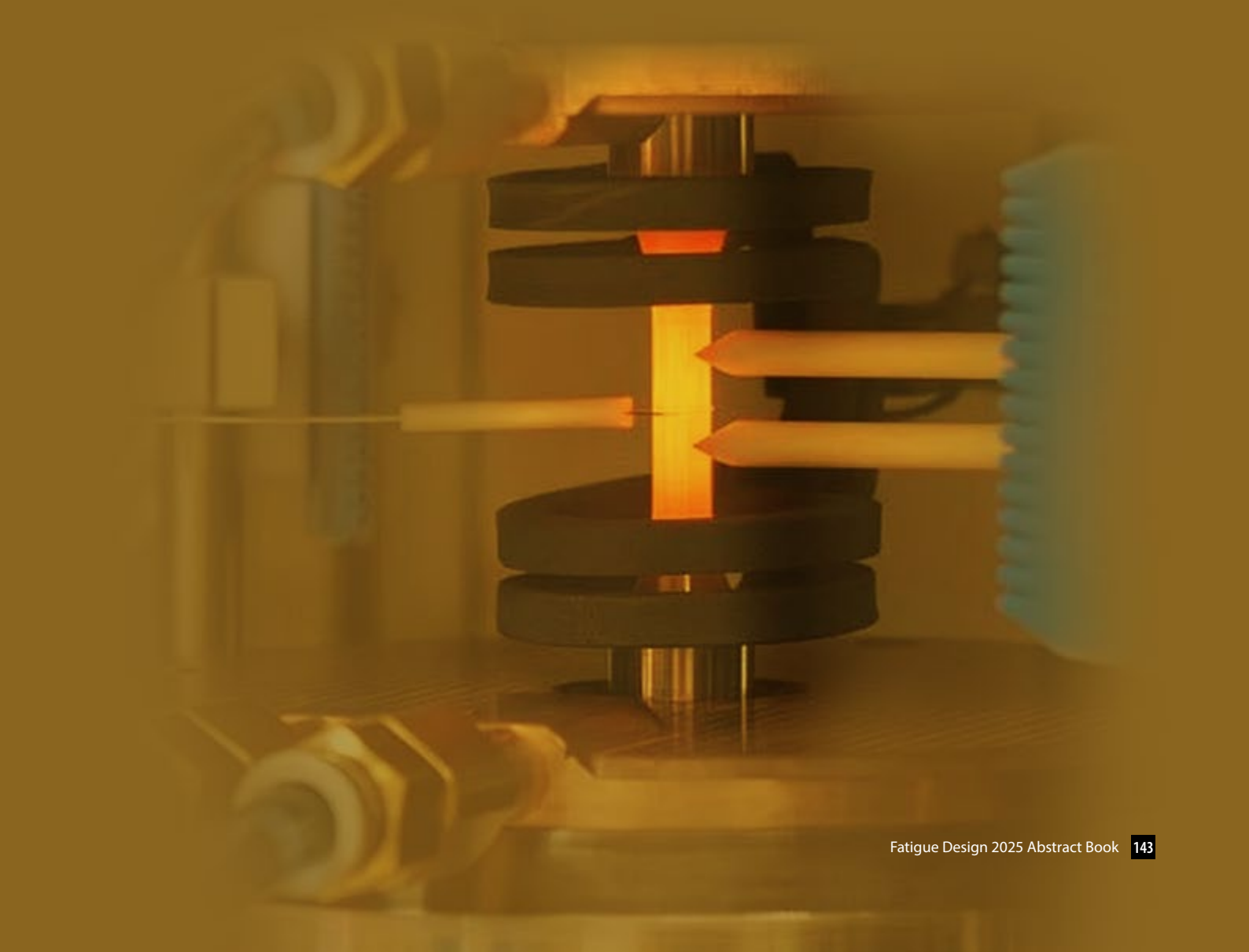
This shows that the sliding amplitude can strongly influence the impact of seawater on fretting fatigue life—either by promoting the beneficial process of interface lubrication, leading to a reduction in mechanical loading, or by activating detrimental corrosion processes that significantly decrease the lifetime. To better understand these effects, a mechanical simulation is proposed to formalize the positive influence of lubrication and, by comparison with experimental results, to quantify the negative effect of corrosion.

S11

Reliability-based Approaches and Probabilistic Methods

Chairmen:

Xavier Hermite & Theo Larue



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FATIGUE DESIGN 2025

FD25-10

Improving fatigue life assessment of scanned nuclear grade weld topologies using elastic-plastic FEA and advanced gradient based fatigue damage parameters

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Fatigue life prediction of scanned weld geometries can be less accurate than prediction using an idealised weld radius. One possible solution is the use of elastic plastic material models. Furthermore, the accuracy can be improved by adjusting the material model retrospectively. However, this cannot be applied to fatigue life prediction in industry. An alternative solution is to introduce additional factors that take into account stress, strain or shear gradients and geometric factors. Scanned weld topologies show radii of up to 0.1mm in the critical areas. These radii can be smaller than the grain size of the base metal. To investigate the difference in accuracy between scanned and idealised weld geometries, we examined the effect of smoothing the scanned surfaces. We also determined different gradients and found the cause of the non-conservative fatigue life prediction in the FDPRM and FDPFFS. The subsequent effect on FDPFS, FDPFGF, FDTSWT was also investigated.

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FD25-87

Probabilistic Fatigue Approach for Complex Vibration Signals. Case Study of Automotive components.

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Structural simulation is gaining momentum in the automotive industry, offering the potential to validate new component designs without lengthy and costly physical prototyping.

Finite Element Analysis (FEA) techniques are powerful to simulate local stress concentrations and identify weak zones - areas prone to cumulative fatigue damage and failure. In the recent years, there have been numerous investigations concerning FEA simulations providing not only the stress level but also the quantification of local fatigue damage accumulation, allowing for the estimation of component durability and time to failure.

Additional methods have been developed in order to overcome the limitations of "deterministic" approaches, by considering the variability associated with fatigue simulation results, by introducing the concept of "Probabilistic Fatigue", also known as "Stochastic Fatigue".

In this paper, we investigate Stochastic Fatigue techniques applied to automotive components undergoing mechanical vibration tests.

The study focus on the intrinsic challenges associated with a stochastic fatigue approach, i.e.:

- the availability of the material characterization
- the difficult of correlating the simulation models
- the choice of the of input parameters to be considered for the Uncertainty Quantification (UQ)

Proposed is a concrete case study based on the simulation of a supporting bracket with known geometrical variations. The geometry is designed in such a way that it allows to consider:

- multiple degree-of-freedom systems
- complex geometry that comes with various source of variability

The fatigue damage of the part undergoing vibration stress from a complex vibration signal

(a Swept-Sine-On-Random SSoR excitation) is initially stimulated via FEA and the fatigue life distribution determined by running multiple simulations by varying certain parameters (the geometry of the bracket, the strength coefficient, the Basquin fatigue exponent, the damping ratio and the surface roughness).

Then, several specimens are vibrated until failure in a testing shaker, and the correlation results are discussed.

By correlating the fatigue variability of FEA-based calculation, the aim of the study is to start from a relatively simple use case to further tackle the issues often encountered in automotive components, which have complex geometry, various resonances and are made from multiple components.

The output of the study is to identify the factors considered during stochastic fatigue simulations and find the best way to correlate FEA results to real vibration tests.

Indeed, given the constraints faced nowadays by the automotive industry, the ultimate goal is the scale-up of the method at industrial level for a routine faster validation (zero test mindset).

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FATIGUE DESIGN 2025

FD25-104

An extension of Active Kriging for Sequential Models to fatigue-loaded Systems under multiple load configurations

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Reliability and sensitivity analyses of fatigue-loaded industrial systems are promising for quantifying the impact of input parameter uncertainties on predicted fatigue life crack initiation. However, this requires first resorting to nonlinear finite element simulations, the results of which are then processed by multiaxial fatigue analyses. The computational cost of nonlinear finite element models generally makes sensitivity and reliability assessment very challenging in an industrial context, as it would require thousands of iterations. This paper aims to evaluate the probability of failure,pf, of a welded substructure of a military vehicle subjected to random loading as the primary objective and then its by-products such as reliability sensitivities.

In order to overcome the computational burden, an adaptation of Active Kriging Monte Carlo Simulation (AK-MCS) to sequential models is proposed and referred to as Active Kriging for Sequential Models (AK-SM). AK-SM introduces a novel enrichment strategy within the AK-MCS framework, leveraging the sequential nature of the numerical chain together with the lower computational cost of the fatigue solver. An imputation criterion based on functional decomposition and variance of the Kriging prediction is used to selectively avoid expensive finite element evaluations and prioritize affordable fatigue post-processor computations.

The results are first demonstrated on a simplified but representative finite element scenario to move toward the industrial case. AK-SM achieves significant reductions in computational cost, ranging from 70% to 90% compared to AK-MCS, while maintaining high accuracy in failure probability estimation. Subsequently, AK-SM is used to solve the industrial problem. Special attention is given to the probabilistic modelling of loading, material and geometrical properties. Reliability sensitivities are also evaluated as a by-product of the approach.

S12

Thermal and Thermo-mechanical Fatigue

Chairmen:

Pierre Osmond & Robin Hauteville

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FATIGUE DESIGN 2025

FD25-12

Fatigue tests of austenitic stainless steel AISI 321 and the weld metal ER 308L in air and high temperature water environment

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Components under water conditions typically suffer more damage than such in an air environment. To estimate the difference quantitatively, strain-controlled fatigue tests in water and in air are carried out with strain amplitudes of 0.3 %, 0.4 %, 0.5 %. The temperature is in both 280 °C, the pressure in the water is 80 bar. The materials investigated are AISI 321 (1.4541) and ER 308L (1.4316) (weld material). In order to keep the strain amplitude in water and in air identical, the global displacement in air is measured with a linear variable differential transformer (LVDT). Out of this recorded LVDT signal, an analytical function for approximation of local strain is formed and then used for control in the associated fatigue test in high temperature water (HTW).

In the tests it could be shown, that the specimens tested in water fail at a lower number of cycles than those in air. Also, a higher strain amplitude leads to higher stresses and to a shorter lifetime. Stresses in ER 308L are lower than those in AISI 321. Moreover, there is a low scatter in the tests, especially when compared with the literature.

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FATIGUE DESIGN 2025

FD25-18

High temperature fatigue behavior of a new PBF-LB/M VDM® 780 alloy

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The actual environmental challenges require a huge effort from all industrial sectors to reduce their emissions of greenhouse gasses and pollutants. In this context, aeronautics is deeply concerned as one of the most emissive industrial sectors (cf. EU Green Deal). The answer to this pressing challenge is complex and involves new fuels and engine concepts, new aerostructures with higher weight-savings, as well as new, energy-efficient, and sustainable manufacturing technologies and materials. A particularly significant contribution could be given by increasing the engine efficiency of airplanes to save fuel and reduce gas emissions. This can be achieved by increasing the engine thermal efficiency, i.e., increasing the turbine inlet temperature. Currently, only single-crystalline cast materials are available to be used for the thermally highest-loaded parts in the gas turbine engine, i.e., the turbine blades in the high-pressure turbine just behind the combustion chamber. These materials rely on a special casting technology, although they lose these original material performances when additively manufactured. In addition, current materials suitable for metal additive manufacturing have a limited range of temperature application. Therefore, the focus is on the development of new materials targeting higher in-service operation temperatures and durability. Recently, a new Ni-based superalloy (VDMÒ 780) has been developed to ensure microstructural stability up to 750 °C. The goal of this work is to provide a deeper understanding of the high temperature fatigue properties of this alloy. This will enable the identification of the maximum operating temperature of this alloy and assess its performance in order to establish its potential in view of a new generation of more efficient aero-engines

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FATIGUE DESIGN 2025

FD25-120

Thermo-mechanical fatigue crack growth of a coated superalloy

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The combustion chamber of aeronautical turbomachines, made from thin sheets of the cobalt-based superalloy Haynes 188 (Ha188), is subjected to cyclic loads caused by repeated engine ignitions, extremely high temperatures from the high-pressure turbine flame, and significant temperature gradients induced by the cooling systems. The inner walls, located in the flame zone, are coated with thermal barriers coatings (TBC), which help protect the walls from high temperatures and increase their thermomechanical resistance. However, these thermal gradients result in severe mechanical stresses. Combined with cyclic loading, they lead to damage in the form of cracks. The development of these cracks is one of the main factors determining the lifetime of the component. Through this study, Safran aims to improve its lifetime prediction models by focusing on a damage-tolerance approach for the coated combustion chamber. The aim of the work is to examine the propagation and evolution of pre-existing cracks to assess the durability of combustion chambers, particularly in the presence of TBC.

The component is subjected to complex thermo-mechanical loads, consisting of variable-amplitude cycles with significant temperature gradients, which can lead to extensive plastic deformation. Furthermore, the presence of a TBC, composed of a NiCrAlY bond coat layer and a yttria-stabilized zirconia ceramic layer applied by APS (Air Plasma Spraying), adds further complexity. The mechanisms of crack propagation under these conditions are not well understood. The challenge of this study is to develop experimental and numerical techniques that accurately represent the loads experienced by the component and replicate the crack propagation observed in coated chambers. Consequently, an experimental test series has been launched to understand the role of each coating layer in crack propagation, using image correlation techniques and infrared thermography. In parallel, finite element numerical methods, informed by experimentally measured fields, are being used to analyze the driving forces that lead to crack propagation. In particular, a phase field approach is implemented to analyze the damage field. This approach is valuable because it can predict the interactions, directions, and paths of multiple cracks from an initial network of experimentally observed micro-cracks, allowing for a detailed analysis of damage mechanisms. New criteria can then be established and applied in remeshing-based methods, facilitating the transition from laboratory results to the length scale of industrial components.

S13

Vibration Fatigue

Chairmen:

Herve Rognon & Sebastien Boudevin

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FATIGUE DESIGN 2025

FD25-1

Fatigue dimensioning of a bearing cap of an electric motor for a commuter aircraft

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An aircraft propeller is directly connected to the rotor shaft of an electric motor. Rotating components are axially supported by a bearing cap. A semi-analytical parametric (second moment of area dependent) mathematical model is built using the Laplace transform. The model is implemented in MATLAB to dimension the bearing cap. Static, modal, frequency response and transient analyses are performed on semi-analytical base. The determined mechanical stresses and deformations are verified in NX NASTRAN by means of the finite element method (FEM). Structural results are used as an input for fatigue calculations performed according to the analytical strength assessment guideline of the Cooperative Research Association for Mechanical Engineering (the FKM guideline). Based on optimal material utilization, a geometry of the bearing cap is developed. Using the fatigue software RIFEST, it is demonstrated that the analyzed geometry can withstand 1E7 load cycles due to propeller excitation.

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FATIGUE DESIGN 2025

FD25-40

Fast and accurate frequency-domain formulation of the Fatemi–Socie critical plane method for multiaxial random loading

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Multiaxial fatigue analysis is crucial in the design and durability assessment of structural components across many engineering areas such as automotive, aerospace, and railway. Among the methods used for the fatigue assessment, Critical Plane approaches, particularly the Fatemi-Socie criterion, are highly effective in identifying critical locations and crack propagation directions for a large variety of structural materials. While this criterion has been extensively validated in the time domain for both proportional and non-proportional loading conditions, its application to multiaxial random loading, especially in the frequency domain, has remained limited.

This study presents a novel and refined formulation of the Fatemi-Socie CP method, adapted for the frequency domain. This approach offers a computationally efficient solution for analyzing fatigue under complex random loadings. The frequency-domain method reinterprets the necessary parameters for calculating the Fatemi-Socie CP factor, utilizing power spectral density (PSD) functions to address the stochastic nature of real-world loading scenarios. A new algorithm for identifying critical planes is introduced by leveraging the covariance matrix, ensuring rapid screening and subsequent detailed analysis on a reduced set of candidate planes.

A comparative analysis between the time and frequency domain results highlights the accuracy and reliability of the proposed approach. The findings confirm that the fatigue life predictions in both domains are closely aligned, reinforcing the robustness of the Fatemi-Socie criterion when adapted to the frequency domain.

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Fatigue Simulations in Automotive Components: the importance of representative validation tests.

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Vibration qualification testing is crucial for automotive manufacturers and suppliers to ensure vehicle reliability. Automotive specifications are designed to rigorously assess component durability against operational stressors, including vibration-induced fatigue, shock loads from impacts, and general wear-out phenomena.

Component qualification typically involves pass/fail testing to verify adherence to customer requirements. Validation of new or redesigned components utilizes both physical bench tests and structural simulations.

Simulation, particularly Finite Element Analysis (FEA), has become integral to the design validation process. FEA not only informs the necessity of physical prototype testing (e.g. shaker tests) but also enables design optimization for enhanced durability and performance prediction.

This paper illustrates a study-case where FEA simulations, carried out during the design validation of a mechatronic component (an electric driven compressor, eDC) were not able to identify the weakness of the initial design, resulting in vibration failure during the final vehicle proving ground test. Measurements on the vehicle showed that the initial validation signal provided for FEA (a sinusoidal vibration at fixed frequency) failed to represent the in-service vibration stress loads on the eDC, which are random in nature.

After an initial description of the issues encountered, the paper will develop the state of the art methods and tools that should be used in order to develop representative vibration tests. The approach, known as "test tailoring method", offers the advantage of truly representing the vibration damage content the components is experienced in the lifetime, but in an accelerated manner.

Additional considerations will interest an in-house software solution that performs quick comparative analysis of vibrations signals, the importance of the vibration mission profiling, and the development of specifications based on physics-of-failure criteria.

By focussing on vibration, the study highlights the importance of validating the design (both on simulation and accelerated bench tests) by the means of representative tests, which need to be correlated to the real in-service stress environment that is affecting the durability of the component.

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Experimental study on the influence of thinness effect and weld quality of non-load carrying welded joints

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Among several parameters affecting the fatigue life of the welded joints, the size effect and weld quality are the main focus of the current study. Fatigue design technical documents consider the thickness effect by reducing the S-N curve for joints thicker than the reference thickness value. Yet, limited attention has been paid to the thinness effect, where the specimens gain life due to decreasing thickness. Understanding the connection between weld profile geometry and fatigue strength is also imperative for assessing welded joints against repeated loads, as geometrical irregularities lead to local stress raising and decrease fatigue life.

In this study, several fatigue test series were performed on non-load carrying welded joints with 2- and 16-mm thicknesses under uniaxial constant amplitude loading, resulting in S-N curves to analyze the influence of thickness on fatigue strength. For each test specimen, the variation of weld shape along the weld seam is measured using a laser scanning tool. Assessment of fatigue test results and weld profile measured data helps better understand the uncertainty and variation in fatigue life and the relationship between fatigue strength with specimen thickness and the weld quality. The results indicate that there is a beneficial effect from reducing thickness and increased weld quality.

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Experimental investigation of the preloading effect on S960 non-load carrying circular flat studs

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Preloading, or potential overloading early in the fatigue spectrum, may redistribute the local residual stress at the weld due to the stress concentration caused by weld geometry, thereby altering the joint's fatigue strength. This study investigates the effect of preloading on the fatigue life of non-load-carrying circular flat studs made from S960 steel. Nominal preloading up to the material's yield strength was applied to induce plastic deformation in the weld transition area. The preloaded specimens were then subjected to constant amplitude fatigue testing, and the results were compared with the fatigue life of specimens without preloading. Finite element simulations based on weld geometry measurements were further used to determine the local stress concentration and its effect from the nominal preloading. The results indicate that preloading improves fatigue life, demonstrating a clear relationship between preloading and fatigue strength, which also highlights the benefits of high-strength steel in welded structures subjected to fatigue.

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FD25-20

Effect of blast-cleaning on the fatigue strength of welded and non-welded constructional details

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Blast cleaning, which is closely related to shot peening, is used to achieve a surface preparation grade of Sa 2.5 prior to the application of corrosion protection coatings. The blasting treatment with sharp-edged blasting material is carried out with defined blasting parameters (blasting pressure, distance and angle). As a result of the blasting treatment, residual compressive stresses are induced near the surface, whereby the surface layer becomes cold-hardened. Findings from the literature show that welded components made of mild structural steels (S235, S355) exhibit an improvement in fatigue strength. Structural details with fillet and butt welds, whose potential crack location is the weld transition notch, can benefit from this. In comparison to post-treatment methods for improving fatigue strength that have already been considered in standards or guidelines (IIW, EN 1993), such as TIG dressing, burr-grinding or high-frequency mechanical impact methods, there are still no generally applicable bonus factors for increasing fatigue strength depending on the structural detail.

The fatigue strength verification is a design driver, particularly for structures subject to high cyclic loads, which ultimately has a significant impact on manufacturing costs due to the number of materials used. In particular for wind turbines, which are becoming larger and larger, and which are subject to longer operating lifetimes, there are high cost pressures.

Towers and foundation structures, which are usually made of structural steel S355, are blast cleaned before the coating work begins. In addition to welded details (circumferential butt welds, fillet welds on attachments), non-welded structural details are also executed. These include drilled holes in the tower wall, through which aircraft warning lights are installed for night visibility signalling, as well as free edges around door openings or cut outs for cable entries. The aim of the paper is to show whether the fatigue strength of welded and non-welded structural details can be improved or whether a reduction in fatigue strength must be accepted by increasing the roughness. For this purpose, fatigue tests are carried out at constant amplitude loading (CAL) in the finite life of the

S-N curve and statistically evaluated according to EN 1993-1-9. It will also be shown that critical compressive preloads might influence the fatigue strength verification. Further findings should result from random tests with variable amplitude loading as well as investigations to qualify the blasting process.

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Fatigue analysis as standard application for every structural analysis with FEM

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The fatigue analysis based on a stress calculation is established as an important addition to the strength calculation with finite elements in industrial use. The results of the fatigue analysis are used to design components and assemblies in lightweight construction and provide a significant gain in knowledge compared to pure stress results.

As a new approach for fatigue analysis, this is fully integrated into a general FEM HPC software. The integration of the fatigue analysis into the FEM solver offers two fundamental advantages for industrial application. Simplified access to the fatigue analysis and the use of the fatigue analysis for new model sizes by efficiency.

The integration enables simplified access. The damage as a result of the fatigue analysis can be very easily calculated and output as an additional secondary result in the stress analysis. The additional effort for input and additional computing time are negligible. Material input is significantly simplified by an SN curve generator based on the FKM guideline. With a few parameters, influencing factors and the FKM material group, the material S-N curve and local S-N curves are determined automatically. Since the damage results are determined directly by the general FEM software and no separate software has to be started after caching the results on disks, the fatigue analysis can be used much more easily in standard industrial processes. This speeds up product development and improves its quality at the same time.

The second major advantage is that the integration saves both computing time and disk space. Interfaces between two different solvers are eliminated, the calculation data is kept in a uniform database, data structures optimized for HPC are used and unnecessary or duplicate data storage is completely avoided. This makes new model sizes possible, since the hard disk space is then sufficient for finer meshed, precise models and these are solved in practical computing times.

The improvements and simplification of handling are clearly shown using a practical example of a calculation process and the S-N curve determination. The very fast run times and low storage space consumption are illustrated using an industrial example of a truck chassis.

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Assessment of Weld Quality and Stress Concentrations in Laser Hybrid Welded Butt Joints Using 3D Scanning and Reverse Engineering

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Fatigue failure often initiates in welded joints under cyclic loading conditions due to high stress concentrations developed by the local weld geometry. The presence of various weld imperfections further amplifies these stress concentrations, increasing the likelihood of fatigue failure. Therefore, assessing weld quality becomes crucial to ensure the structural integrity of welded components. One of the most effective methods for evaluating weld quality is 3D laser scanning technology, which provides a precise and detailed profile of the weld. This technique allows for the identification of weld imperfections and highlights critical areas with high stress concentrations, helping to predict potential failure areas. However, the complex geometry of welds makes it challenging to determine stress concentrations on the weld surface accurately from 3D scan data.

In this study, we present a method to assess weld quality and numerically determine stress concentrations in laser-hybrid-welded butt joints with weld imperfections using 3D scans. A total of 76 specimens were scanned with a high-resolution 3D laser scanner to capture the weld geometry in detail. The scan data was then used to evaluate weld quality according to the ISO 12932:2013 standard and to create numerical models for 3D finite element (FE) analysis. The reverse engineering method was used to convert the scan results into numerical models. Additionally, fatigue tests were conducted to observe the actual failure locations in each specimen and compare them with the failure locations predicted by the 3D FE analysis. The findings highlight the potential of this method in identifying weld imperfections, determining stress concentrations on weld surfaces, and predicting fatigue failure locations based on 3D scans.

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S-N Performance of Horizontally Built LPBF Ti6Al4V Fatigue Samples: Effect of Support Structures and Direction Dependent Surface Textures

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Laser Powder Bed Fusion (LPBF) is an Additive Manufacturing (AM) process that results in parts of high geometrical fidelity. This makes it attractive for the fabrication of intricate components. Fatigue design considerations during the in-process fabrication process can affect the S-N curve fatigue performance outcome. A review of the factors influencing fatigue performance such as build direction, as-built surface roughness, and heat treatment will be presented. For As-built fatigue test specimens, the techniques used in the removal of support structures, surface preparations can have a significant impact on the fatigue performance. Support structure planning and removal must be factored into the build job from the beginning and can determine the optimal build orientation. AM part qualification strategies are needed to accelerate AM part adoption for industrial applications. This contribution will provide insight on fatigue design considerations for in-process and part qualification strategies for LPBF process.

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Assessment of stress concentration factors of welded joints based on 2D- and 3D-reverse engineering

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The surface geometry and the stress concentration of welded joints shows a large variation and is individual for each joint at each position, especially at welding joints with start-stop-positions (intermittent welds). These positions are geometrical weak points of welded joints due to high stress concentrations. The stress concentration factors (SCF) at such positions (with flank angles > 90°) could usually not evaluated by former parametrized SCF-equations. For this reason, a reverse engineering approach was used based on the translation of 3D-surface scans (point clouds) into Finite Element Analysis (FEA) for the determination of SCF. An artificial neural network was used to connect the point clouds from 3D-scans to the evaluated SCF. A good correlation was determined between the locations of crack initiation and the evaluated SCF at the welds with start-stop-positions.

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'Total-Life' method: achieving accurate fatigue life predictions by combining strain-life and fracture mechanics

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All components that fail through fatigue undergo a two-stage failure process: the first part of a component's life is spent initiating one or more cracks (crack initiation stage), after this stage the crack(s) propagates to failure (crack propagation or crack growth stage). The proportion between crack initiation and crack growth depends on material, type of structure, application, etc.

Traditionally, the two stages have been analysed using different physical models: generally, a strain-life (E-N) model for the crack initiation stage and a Linear Elastic Fracture Mechanics/Elastic-Plastic Fracture Mechanics (LEFM/EPFM) model for the crack propagation stage. Furthermore, common simulation methods focus either on the initiation or the propagation stage. However, this might produce inaccurate fatigue life predictions in situations where both stages are not negligible compared to the other. This is true for welded structures, lightweight jointed structures and lightweight cast components that are becoming increasingly popular and necessary to address the need for more sustainable methods of transportation.

This paper presents a unified method for fatigue life estimation that combines both the initiation and the propagation stage. The proposed method, also called 'Total-Life', takes advantage of principles of both strain-life and fracture mechanics by combining them together and with a state-of-the-art multiaxial crack-tip plasticity model to account for mean-stress and overload retardation effects. The benefits of the 'Total-Life' method compared to traditional fatigue analysis methods are discussed. In order to exploit the potential of the presented method and allow its usage in a CAE environment, the 'Total-life' method has been implemented into a software package. The required inputs such as applied loading, finite element modelling techniques, material properties, residual stresses, etc. are also described.

Finally, the 'Total-Life' method is applied to estimate the fatigue life of machined and welded specimens sharing the same complex shape. The results of the aforementioned analyses showed a good correlation with experimental results.

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Fatigue life assessment of dissimilar and homogeneous LPBF AISI 316 L butt welded joints

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The current industrial scenario, especially in the automotive, nuclear and aerospace sectors, demands the use of lightweight structures. In this context, topology optimization and Additive Manufacturing (AM) technologies play a fundamental role. Differently from traditional methods, AM drawbacks are the high production costs and the limited dimensions of produced parts due to the presently available printing volumes. The latter limitation particularly affects the industry of amusement parks, where there is a need to design large structures. To exploit the benefits of AM in such cases, it is necessary to join two (or more) AM-produced components, or AM components with parts manufactured using traditional processes. When a joint combines a wrought part with an additive one of the same material, it is called dissimilar due to the microstructure. Among all the joining technologies for metallic materials, welding stands out as one of the most effective due to its cost-efficiency and its "weight-efficiency", since it does not increase the weight or the number of components in the final piece. The technological and metallurgical feasibility of joints between AM parts through arc welding has already been demonstrated in the literature. However, a guideline for the fatigue design of such joints has not been formalized yet.

In this study, the fatigue strength of dissimilar and additive-additive welded joints in austenitic stainless steel was investigated. A reanalysis of experimental data obtained from the literature and relevant to 316 L butt welded joints was conducted using the nominal stress approach. It was found that the existing standards for structural steel joints do not accurately capture the behaviour of these joints. Afterwards, the data were reanalysed using the Peak Stress Method (PSM), which is an engineering local approach based on the Notch Stress Intensity Factor (NSIF) estimated through linear elastic FE analyses with coarse meshes. By converting the literature data from the nominal stress approach to the PSM, a new fatigue design scatter band was calibrated specifically for this class of steels. Then, the new fatigue design curves have been validated against experimental literature data generated from dissimilar and additive-additive butt welded joints, which demonstrated fatigue strength comparable to that of traditional joints belonging to the same class of steels. In addition, some experimental tests were performed on 316 L butt welded joints. The tests included both traditional and dissimilar welded joints. The obtained experimental data are in good agreement with the results found in the literature.

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Effect of Phosphorus Content on Fatigue Crack Acceleration in Martensitic Steel under High-Pressure Hydrogen Gas Environment

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Fatigue crack propagation in body-centered cubic structured steels, such as carbon and low alloy steels, is significantly accelerated in hydrogen environments. Frequency dependence is a crucial factor in fatigue life design, warranting investigation across various steel types. Research has shown that in low to medium strength steels, with ultimate tensile strengths below 900 MPa, the rate of crack acceleration remains relatively constant regardless of the loading frequency. In steels with tensile strengths above 900 MPa, the crack acceleration rate is known to increase with decreasing load frequency. One of the factors contributing to this phenomenon is the presence of impurity elements such as phosphorus. This study investigates the effects of phosphorus content and tempering temperature on fatigue crack growth in martensitic steel in a 90 MPa hydrogen gas environment. By focusing on hydrogen embrittlement resistance, we analyzed the effects of varying phosphorus content and tempering temperatures on fatigue crack propagation in hydrogen compared to air. The research highlights that specimens with higher phosphorus content and lower tempering temperatures exhibit a greater area fraction of intergranular fracture along pre-austenite grain boundaries (PAGBs) and an accelerated FCG rate in hydrogen compared to air. Our findings also demonstrate that lower phosphorus content and higher tempering temperatures significantly enhance resistance to hydrogen embrittlement, resulting in reduced fatigue crack growth (FCG) rates in hydrogen. Therefore, the critical role of material composition and thermal treatment in mitigating the adverse effects of hydrogen on fatigue performance in high-pressure environments provides valuable insights for designing more durable materials for hydrogen-related applications.

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Effect of Hydrogen on Torsional Fatigue Behavior of Ni-based Superalloy 718

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Ni-based superalloy 718 (Alloy 718) has been extensively used in key components of rocket engines, which are subjected to not only uniaxial but also multiaxial fatigue loading. In addition, this alloy is frequently exposed to hydrogen-rich environments in liquid hydrogen-fueled rocket engines. According to a NASA report on the safety standards of materials for hydrogen use, Alloy 718 is classified as "extremely embrittled" with regard to hydrogen susceptibility. Additionally, it is known that the fatigue limit of Alloy 718 under torsional fatigue loading in air is determined by the non-propagating condition of a small, shear-mode fatigue crack. However, the effect of hydrogen on the torsional fatigue behavior of this alloy remains unclear.

In this study, torsional fatigue tests were conducted using a resonance-type fatigue-testing machine, operated at a stress ratio of −1 and a test frequency of 50 Hz. Round-bar fatigue specimens of Alloy 718 were fabricated, with the gauge sections polished using emery paper and subsequently buffed with diamond paste. Some specimens were subjected to hydrogen charging (H-charging) by exposure to 100 MPa hydrogen gas at 270°C for 200 h. The torsional fatigue limit was determined by the shear stress amplitude at which a specimen did not fail after 108 cycles. All tests were carried out in ambient air at room temperature. The tests were periodically halted to examine the propagation of fatigue cracks using the plastic replica method. After the tests, the fracture surfaces of some failed specimens were examined using a scanning electron microscope (SEM).

The test results revealed that the fatigue life of H-charged specimens was shorter than that of non-charged specimens under relatively high stress amplitudes. In addition, surface crack observations using the plastic replica method and fractographic analysis using SEM revealed a higher fatigue crack growth rate and the presence of multiple facets across a wider area at the crack initiation site in H-charged specimens, respectively, under relatively high stress amplitudes. Conversely, the influence of hydrogen on the fatigue limit of H-charged specimens was minimal. Furthermore, the fatigue limit was determined as the threshold condition for a small, shear-mode fatigue crack, consistent with the test results of non-charged specimens. Further investigation is ongoing to elucidate the underlying mechanisms of these phenomena, particularly in relation to hydrogen-dislocation interactions.

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FD25-77

Effect of waveform on fatigue crack growth behavior of pipeline steel X60 in high-pressure hydrogen gas

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Hydrogen is gaining attention as a secondary energy source for achieving a decarbonized society. Establishing means for transporting large quantities of hydrogen at low cost is essential for its widespread adoption. One such method under consideration is transporting hydrogen gas using existing natural gas pipelines. However, pipeline steel generally has a body-centered cubic (BCC) structure, which is considered highly hydrogen-sensitive. Concerns exist regarding hydrogen embrittlement caused by high-pressure hydrogen gas, prompting research in various countries to ensure safe operation.

Pipelines laid in cold regions are exposed to sub-freezing temperatures, necessitating a clear understanding of the effects of low-temperature hydrogen on various strength properties to ensure safety. While experimental data on pipeline steel's tensile properties, fatigue crack growth characteristics, and fracture toughness under ambient hydrogen conditions are relatively abundant, no reports exist on the effects of low-temperature hydrogen.

The authors previously investigated the effect of a low-temperature hydrogen gas environment on the fatigue crack growth characteristics of pipeline steel API 5L X60. The results showed that at room temperature and −10°C, the fatigue crack growth acceleration rate ranged from approximately 10 to 25 times and remained nearly constant regardless of the load frequency. However, at −20°C and −30°C, acceleration of about 10 times was confirmed at f = 0.1 and 1 Hz, but no acceleration was observed at f = 0.01 Hz. The crack growth rate was found to be almost equivalent in air and hydrogen gas. Furthermore, observations of the crack tip after testing revealed that the tip became sharper when acceleration occurred and blunted when no acceleration occurred.

Previous studies have reported that in carbon steel and low-alloy steel, the crack growth rate in low-frequency ranges under room-temperature hydrogen gas is equivalent to that in air. However, the mechanism behind this phenomenon remains unclear. Furthermore, while pipelines typically maintain constant internal pressure, periodic maintenance involves fluctuations in gas pressure, subjecting them to repeated loading.

Therefore, it is important to understand the effect of the hydrogen environment on material strength when long-term loading or low-frequency cyclic loading occurs. Therefore, as part of an effort to clarify the conditions and mechanism for this phenomenon, this study investigated the effects of load waveform and load holding on crack tip deformation behavior in a high-pressure hydrogen gas environment.

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Effect of loading waveforms on fatigue crack growth in pipeline steel in high pressure hydrogen gas

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In recent years, hydrogen energy has gained attention as a solution to the increasingly severe issue of global warming, with underway plans to develop hydrogen infrastructure using pipelines for transport. Pipelines are subjected to cyclic stress due to gradual fluctuations in the internal hydrogen gas pressure during operation. In pressurized hydrogen gas environment, the strength of materials decreases compared to that in air—a phenomenon known as hydrogen embrittlement—which can cause crack propagation even under small stresses. Therefore, it is essential to understand the effects of hydrogen embrittlement caused by high-pressure hydrogen gas in pipelines and incorporate this knowledge into strength design to ensure safety and potentially reduce costs.

However, loading patterns used in previous studies have been biased, either by continuously loading specimens until fracture, as in tensile and fracture toughness tests, or by repeatedly applying very small sinusoidal stresses compared to the yield stress, as in fatigue crack growth tests. This study conducted cyclic loading and constant load-holding tests using triangular and trapezoidal waveforms with high loads and low frequencies under a high-pressure hydrogen gas, with the goal of simulating hydrogen pipeline operation in a more realistic way. The test results showed that crack growth was greater in tests using triangular waveforms than in those using trapezoidal waveforms, which included a load-holding phase.

Further post-mortem analysis included fracture surface observation, three-dimensional measurement of the fracture surface, and FEM analysis to investigate the effects of cyclic loading and load-holding on crack propagation from a practical perspective. Additionally, the Crack Mouth Opening Displacement (CMOD) value, measured with a clip-on gauge, gradually increased during load-holding in high-pressure hydrogen gas. To verify the accuracy of the measurements, the drift of the clip-on gauge was checked by leaving the specimen unloaded in high-pressure hydrogen gas for an extended period. The series of experiments suggested the possibility of hydrogen-enhanced crack blunting ahead of the crack tip though further examination is necessary to confirm its validity.

Moreover, deformed microstructures in the vicinity of the crack tip has been investigated in more details using Electron Channeling Contrast Imaging (ECCI) on specimens subjected to constant load-holding tests in both air and hydrogen gas. Based on these tests and observations, the potential of creep induced crack evolution in materials under high-pressure hydrogen gas was also examined.

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FD25-93

Contribution of thermometry for the study of metal structures with process induced defects in high cycle fatigue

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High-cycle fatigue of metallic materials is an insidious phenomenon, and therefore particularly critical for the structural integrity of components in service. Despite the considerable progress made since the first documentation of fatigue failure in the 19th century, structural fatigue design remains a major concern. In recent years, some research teams have focused on characterising high-cycle fatigue properties using thermometry techniques. Using a multi-scale approach which proposes a link between self-heating under cyclic loading and specific dissipative mechanisms, it is possible, for a wide range of materials, to identify a Weibull model describing the material's S-N curve and associated dispersion. Since this modelling framework naturally takes into account volume effects, it is possible to study the fatigue behaviour of a complete structure under in-service loading.

In the particular case of large castings (e.g. marine propeller blade), the existence of material heterogeneities (volume defects, microstructure variations) can have a considerable effect on fatigue behaviour [3,4]. Using a probabilistic approach and a coherent experimental framework, the present study suggests to set up a numerical tool for the fatigue life forecast of structures, considering defects specific to the process.

Firstly, an experimental protocol is proposed in order to carry out a self-heating test on a heterogeneous (presence of defects and microstructure variation) material in rotary bending. Secondly, the thermodynamic framework of the test is discussed and a custom post-processing of infrared data is suggested for the assessment of the material's dissipative behaviour. Finally, a link is proposed towards fatigue via a probabilistic approach, and validated by comparison with independent experimental fatigue data.

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FD25-98

Effect of Temperature and Hydrogen Coupling on the Fatigue Behaviour of an Austenitic Steel Used for Bolts at Low Temperatures

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Austenitic alloys are among the most commonly used materials for applications that require fatigue resistance in gaseous hydrogen environments. The literature consensus indicates that austenitic steels have a critical hydrogen embrittlement temperature of -80°C; however, this conclusion is primarily based on tensile data, with very few studies examining fatigue loadings. With the anticipated increase in hydrogen usage in energy mixes, this knowledge is crucial for the fatigue design of components used for cryogenic hydrogen storage, such as bolts in liquid hydrogen tanks. Cetim aims to assess how hydrogen and temperature coupling affects the fatigue behaviour of an austenitic steel used specifically in bolts operating in low-temperature environments.

To investigate the effects of hydrogen at low temperatures on the fatigue behaviour of this austenitic alloy, a fatigue campaign was conducted under three temperature conditions: ambient, -80°C, and -190°C, with two different hydrogen gas precharging conditions: one representative of the actual usage conditions and one more severe. Physicochemical characterizations were performed on the material to obtain a thorough understanding of the parameters that could influence its behaviour. A comprehensive study of the results was carried out using Wöhler curves and analyses of damage mechanisms on fracture surfaces.

By comparing the findings with existing literature, this study will contribute to a deeper understanding of the temperature dependence of hydrogen susceptibility in austenitic alloys. This enhanced knowledge will help strengthen the case for using these materials in industrial components, ensuring their reliability and performance under varying conditions.

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Influence of the load ratio (R) on the fatigue limit of Inconel 718 DA in presence of artificial defect

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The load ratio is an extrinsic parameter that influences the crack propagation threshold (ΔKth) and the fatigue limit (σD). This work focuses on the influence of the load ratio in the case of NI718-DA alloy containing a surface defect at fatigue limit and in the region near the fatigue crack propagation threshold. Fatigue tests were conducted at different load ratios R = -1, 0.1, 0.4, and 0.7, on both the materials, with and without artificial spherical defect, by using the Locati step by step method. Relatively few studies have been carried out up to now on the influence of the load ratio on the Kitagawa diagram for this material.

Regarding crack propagation threshold, fatigue crack growth tests were carried out using the "Standard load reduction method" at different load ratios (R = 0.1 and 0.7). The closure measurements associated with each test were used to find the effective curve (i.e. da/dN -ΔKeff curves). The literature indicates that the effective threshold, known as intrinsic value, may not be dependent on the load ratio.

The obtained results were in accordance with the literature, where a decrease of the fatigue limit can be observed with respect to the mean stress for both specimens (with or without defect). The means stress effect was analyzed by classical models, but the correlation was not quite good. The fatigue crack growth tests confirmed the existence of an intrinsic threshold of 3MPa√m.The Kitagawa diagram obtained from the fatigue tests, defect size ranging from √area = 116-470µm, shows a slope close to -1/2 for R = 0.1 and 0.7 similar to the one described by fracture mechanics; but for the other R, the slope was different. The observation of the fracture surface showed a very localized initiation site, not homogeneous all around the defect area. Based on these observations, considering the defect as an initial crack with a spherical shape turns out to be inappropriate.

To improve the understanding of the links between the threshold value and the damage initiation in presence of defects with respect to the load ratio, we will investigate the mechanisms that govern the lifespan of the material during the fatigue test, by using the replica tests. To understand the effect of load ratio and compare the experimental results, the finite element method will be used, -taking into account plasticity- and fatigue criteria.

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FD25-117

Influence of low temperature on the high cycle fatigue of austenitic steels under ratcheting conditions

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The behavior and performance of austenitic steels have been the subject of numerous studies in literature, particularly in the context of the development of pressure components, for instance in the nuclear industry. Regarding behavior, the cyclic stress-strain relation of these materials under various mechanical and thermal loading conditions has been extensively studied with the aim of predicting the response of components subjected to such loading and preventing the occurrence of the ratcheting phenomenon, which can lead to rapid structural failure. In addition, the fatigue performance of these materials under controlled loading conditions has been widely characterized to enable the evaluation of the fatigue lifetime of components. Historically, the study of fatigue properties under ratcheting conditions has been limited because (i) the design criteria usually used for pressure equipment exclude operation under ratcheting conditions, and (ii) the behavior observed under ratcheting conditions is not conducive to studying damage mechanisms.

However, constraints associated with the implementation of fatigue tests can lead to "undergo" ratcheting behavior, notably when fatigue testing machine do not allow for the application of fully reversed loading. This is typically the case for fatigue tests conducted in hydrogen environment. The work presented here focuses on the behavior and fatigue performance of austenitic steels submitted to a positive load ratio (R = 0.1), leading to ratcheting. The effect of low temperatures is studied over a temperature range from -120°C to 100°C in the context of the development of pressure equipment. The effect of temperature on ratcheting behavior is analyzed in terms of cyclic hardening and ratcheting rate, with a particular attention to the interaction between ratcheting behavior and martensitic transformation induced by deformation in the high-cycle fatigue regime. Additionally, the effect of temperature on fatigue performance is characterized and discussed to identify the most suitable fatigue indicator parameter to describe the effect of loading and temperature under ratcheting conditions.

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FD25-123

Significant improvement of the fatigue performance of ER70S-6 WAAM un-milled structures: A Cu/Ni multilayer nanotechnology approach

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Fatigue is responsible for approximately 80% of all structural failures1, representing a significant concern within the field of civil engineering. In recent years, the incorporation of 3D printing into steel construction practices has gained considerable traction. Surface notches associated with the welding process are unavoidably generated when the layers are deposited sequentially. These surface notches exhibit substantial stress concentrations, which act as the origins for fatigue crack propagation1,3. The classification into a FAT class is profoundly influenced by the stress concentration levels found at these notches. The innovative research approach focuses on the direct management of the critical residual stresses by introducing residual compressive stresses at the surface level by utilizing a Cu/Ni nanostructured metallic multilayer film (NMM)4. The compressive residual stresses that have been established reach the yield stress of the base material, thus providing an effective counteraction to the tension residual stresses that are inherent to the manufacturing process. Based on a Monte Carlo simulation, the un-milled surface of a WAAM component is designated as FAT 1253. Running research is directed towards determining a FAT classification using physical samples. Subsequently, identical samples are post-print-treated with NMM and subjected to a series of fatigue tests. The NMM application on the 3D-printed structure, e.g. on surfaces which are expected to be subjected to tension-tension fatigue, potentially leads to a multifold extension of service life, hence, contributing to structural integrity of 3D-printed steel components.

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FD25-125

Merging Nano and Macro Structure Design: Opportunities for the Structural Integrity of Steel Infrastructure

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Merging the macro-level design with the nano-level design in structural engineering, hence, using the superior properties of nanostructured metallic multilayers for protecting fatigue-critical joints of the macrostructure and ensuring the structural integrity of the steel infrastructure are the objectves of a research effort at TU Hamburg1-3.

Nanostructured metallic multilayers have significantly higher strength, fatigue resistance and ductility than monolithic homogeneous metal cross sections. The superior structural properties of these nanostructured cross sections are known, and so it is surprising why no attempt has been made to date to use nanostructured cross sections in macro cross sections in structural engineering to improve the cross section properties. This paper links the advantages of nanostructured multilayers with the needs of homogeneous metallic macro-cross sections and examines the question to which extent the high-performance material nanolaminate can compensate for the structural weak parts of metallic infrastructure. The welded joint subjected to fatigue is addressed as vulnerable part of metallic infrastructure. The article provides insights on how nanostructured multilayer can potentially contribute to the future of steel construction, further, how nanostructured multilayer can potentially affect fatigue design. The design as well as the maintenance of cyclically loaded metallic infra-structures, such as bridges and offshore wind turbines, are discussed herein and it is shown how sustainability, resource conservation, reduction of CO2 footprint, readiness, security of supply and economic viability of steel infrastructure can potentially be achieved.

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FD25-132

Microstructure degradation in the Silchrome 1 steel by high temperature VHCF: a case study

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The different components of internal combustion engines, especially valves, operate in complex conditions. High temperature, cyclic thermal and mechanical loading, and corrosive medium are interactive damage sources. This requires optimizing the choice of material to satisfy their long-durability and high reliability to avoid valve failures. Silchrome 1, a martensitic steel with the chemical composition - C 0.40–0.50, Cr 8.00–10.00, Si 2.70–3.30, Mn 0.50–1.50, P max 0.040, S max 0.030, Ni max 0.50 wt% - appeared to be suitable for valve fabrication because it maintains its properties up to 600–650 °C under a high dynamic load. Even though Silchrome 1 has been designed and used since the 1920s and it is still in use today.

The present communication focuses on an investigation of two exhaust valves fabricated in 1942 for a Harley-Davidson WLA/WLC motorcycle. The first one is unused and comes from a surplus replacement kit. The second one has been extracted from a motor which motorcycle has driven for 300 000 km.

The investigation consisted in a deep analysis of the microstructure of both valves especially in the stem and in the head. It is shown that the evolution of the microhardness along the valve from the stem top to the head bottom was constant in the unused valve but exhibited a marked drop in the head area of the used valve. SEM-EBSD analysis point out grain coarsening and carbide growth in the valve fillet. Comparison with the microstructure of the stem which is essentially only thermally loaded allowed concluding that the modification of the microstructure resulted from cyclic loading at high temperature. Additional fatigue indicators were also found by TEM analysis which revealed the presence of twist boundaries typical of high temperature fatigue.

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FD25-137

Visually Readable Sensors for Fatigue Life Monitoring of Safety Critical Structures

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A novel polypropylene (PP) fatigue sensor has been developed to provide real-time feedback and predictions for structural health monitoring by detecting crack propagation. This sensor offers advantages such as cost-effectiveness, colourability, ease of attachment, and the ability to be visually inspected without specialised equipment. While the sensor demonstrates excellent performance in fatigue life prediction, its environmental adaptability and reliability under extreme conditions require further investigation. This study evaluates the performance of the new PP fatigue sensor during the crack propagation phase. Fatigue crack propagation experiments were conducted using a servo-hydraulic testing machine (Instron 8801) to analyse the sensor's response based on fracture mechanics principles. Additionally, a comparative analysis was performed to assess the advantages and limitations of the PP fatigue sensor against traditional metallic sensors in the context of total fatigue life monitoring.

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FD25-155

On the Role of Hydrogen in Plasticity Mechanisms Associated with Cyclic Creep of a 304L austenitic stainless steel

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Decarbonized hydrogen is a key energy carrier in the transition to low-carbon energy systems. Austenitic stainless steels, widely used in hydrogen-related applications, exhibit good resistance to embrittlement, though not complete immunity. This study investigates the effect of hydrogen on the ratcheting behavior of 304L stainless steel at room temperature. The material was pre-charged with 100 wppm solute hydrogen in a pressurized H_2 environment. Three loading paths—single-step, increasing, and decreasing multi-step—were applied to evaluate the influence of maximum and mean stresses on the steady-state cyclic creep rate. Flow stress decomposition (back stress and effective stress) and TEM analyses revealed changes in dislocation structures and phase transformation as a function of mechanical loading and hydrogen content. Additionally, EBSD and XRD quantified phase evolution and linked surface and bulk responses. Hydrogen caused solid-solution hardening by hindering dislocation motion and influenced the creep rate in a stress-dependent manner—either accelerating or decelerating it—through its combined effect with strain-induced phase transformation, whose dominant pathway ($\gamma \rightarrow \alpha'$ or $\gamma \rightarrow \varepsilon \rightarrow \alpha'$) depends on both hydrogen presence and applied stress

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The very high cycle fatigue behaviour of case-carburised steel for gear applications using vibration-based testing

Thomas Banide, Hugo Heyraud, Myriam Brochu, Annie Ross, Vincent Argoud, Charlie Poulat, Louis Augustins, Damien Herisson, Etienne Pessard, Franck Morel, Sophie Cazottes, Jean-Yves Buffière

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Vibration-based structural fatigue testing is an unconventional test type for which a cantilever-mounted specimen is excited at the natural frequency of one of its resonant modes. This kind of testing offers several advantages, one of which is that the deformed shape of the specimen at resonance allows the generation of a desired cyclic stress field at high frequencies, which can exceed 1,000 Hz, significantly reducing testing times. In the field of Very High Cycle Fatigue (VHCF), minimizing the test time is critical as tests exceeding 107 cycles generally take several days using conventional machines. This can be reduced to a few hours for vibration-based testing. VHCF behaviour of case-carburised steel used for gear applications needs to be understood and investigated as these type of applications can reach 107 cycles in only a few hours of service. Thus, the use of vibration-based fatigue testing is relevant for this application. In this study, notched specimens used for conventional bending testing were mounted on an electrodynamic shaker. The specimens were specifically designed to reproduce the stress field at the root of a gear tooth in-service. The resonant frequency of the tested mode of the specimen was around 1,300 Hz, making it possible to reach VHCF in around two hours. Results of fatigue testing showed good correlation with those obtained with conventional fully reversed bending tests (100 Hz) using the same specimens. This test methodology paves the way for in-depth studies of VHCF bending behaviour of case-carburised steel specimens in reasonable testing times.

References

Authors	Abstract number
Oudriss, Abdelali	126
Niesłony, Adam	40
El Bartali, Ahmed	55
Li, Aijia	138
Kamada, Akichika	77
Shibata, Akinobu	75
Campagnolo, Alberto	37, 45, 67, 68
Visentin, Alberto	45
Marano, Aldo	126
Tognan, Alessandro	139
Lanzutti, Alex	139
Holch, Alexander	20
Boulzaguet, Alexandre	43
Juin, Alexian	43
Arora, Aman	75
Chabod, Amaury	38, 49, 61, 62
Danchenko, Anastasiia	59, 60
Beyer, André	88
Simonneau, André	47
Chiocca, Andrea	40
Halfpenny, Andrew	61, 62, 152
Gourgues-Lorenzon, Anne-Françoise	136
Ross, Annie	156
Ezanno, Anthony	93, 143
Millecamps, Antoine	55
Alvaro, Antonio	83
Isaac, Arnaud	16
Thibault, Arthur	55
Duraipandi, Arumugapandian	64
Mayya, Ashwij	115
El Moutaouakkil, Ayoub	97, 98
Lamothe, Baptiste	93
Nyhus, Bard	83
Luckett, Barry	73

Authors	Abstract number
Tchamou, Batina	99
Amini, Behnaz	56
Causse, Benjamin	33
Delattre, Benoit	34
Verquin, Benoit	111
Rehmer, Birgit	18
Tsobmene, Bonickel	100
Le Pannerer, Brice	120
Depale, Bruno	81
Levieil, Bruno	143
Burton, Camille	99
Gandiolle, Camille	41
Nehls, Carl Christian	20
Payares-Asprino, Carolina	24
Mattrand, Cécile	104
Doudard, Cédric	93, 108, 143
Caer, Célia	102
Bianchetti, Charles	43
Poulat, Charlie	156
Yanming, Chen	47
Huang, Cheng	27
Danekas, Christian	46
Martinez, Christian Felix	24
Garnier, Christian	138
Bleicher, Christoph	109
Tegos, Christos	35
Tonetta, Claudio	33
Keller, Clément	138
Jacquemoud, Clémentine	151
Bagni, Cristian	61, 62
Jbily, Dalia	47
Herisson, Damien	156
Le Ba, Danh	81
Bellett, Daniel	63, 99
Fuchs, Daniel	129

References

Authors	Abstract number
Schwarz, Hannes	6
Ahmad, Hayder	73
Nouri, Hedi	136
Remes, Heikki	8
Proudhon, Henry	135
Kawashima, Hideto	74
Matsunaga, Hisao	51, 74, 75, 76, 77, 83, 150
Heyraud, Hugo	156
Le Mestreallan, Hugo	43
Sistach, Hugo	135
Koutiri, Imade	96
Lotsberg, Inge	20
Serrano-Munoz, Itziar	18
Bouhattate, Jamaa	126
Najd, Jamal	158
Haubrich, Jan	18
Papuga, Jan	30, 101
Schubnell, Jan	59, 60, 84
Vogt, Jean-Bernard	132
Roux, Jean-Christophe	154
Carton, Jean-François	63
Witz, Jean-François	55
Scherer, Jean-Michel	120
Buffière, Jean-Yves	156
Disson, Jean-Yves	92
Plets, Jelle	65
Bouquerel, Jeremie	132
Van Wittenberghe, Jeroen	71, 118
Gussone, Joachim	18
Filho, Joao	44
Rech, Joël	38
Krautheimer, Johannes	59
Rosenberger, Johannes	60
Pang, John Hock Lye	53, 54

Authors	Abstract number
Yates, John	73
Hinrichs, Jonas	58
Baumgartner, Jörg	84, 91, 105
Fitoussi, Joseph	121
Havia, Juho	86
Baroth, Julien	16
Beaudet, Julien	72
Croquet, Julien	119
Louge, Julien	93
Kruse, Julius	18
Rudolph, Jürgen	10, 69
Munk, Juri	18
Lipiäinen, Kalle	15, 86
Harb, Kamal	16
Stahl, Karsten	129
Sridhar, Karthikeyan	87
Mouradian, Kevin	88
Heide, Klaas Maximilian	46
Henkel, Knuth-Michael	42, 58
Hectors, Kris	65
Fouche, Laëtitia	104
Giraud, Landry	154
Hakansson, Lars	39
Larippe, Laure	41
Loire, Laureline	72
Dastugue, Laurent	21
De Baglion, Laurent	70
Dolle, Laurent	128
Gornet, Laurent	141
Ponson, Laurent	115
Guilmois, Lauriane	157
Serri, Leonardo	101
Gardner, Leroy	27
Milne, Lewis	28, 110
Li, Lingzhen	27

References

Notes

Notes

Notes

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